Investigation of Mitigation and Detection Methods of Open Phase Conditions (OPCs) in Nuclear Power Plants based on the Operating Experience

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ABSTRACT

Safety in a Nuclear Power Plant (NPP) is of utmost importance, as the implications of a nuclear event have dire consequences on people, animals, and the environment and on unborn generations. This dissertation is about Open Phase Conditions (OPCs), which occur when one or two of the three electrical phases are lost or open circuited, e.g. one circuit breaker phase doesn't open or close. The study of this condition is important, as it can affect important-to-safety equipment, which is critical to the safe shutdown systems of the reactor in a nuclear power plant. The OPC can occur in the transmission (TX) switchyard or at the transformers connected to the nuclear plant. It also has the capability to make the offsite supply inoperable, which is the alternate source of power for the nuclear safety systems.

As many as sixteen (16) cases of Open Phase events have occurred in different countries worldwide from 1994 till 2015. An event also occurred in the Koeberg Nuclear Power Station (KNPS) in South Africa on the 11th November 2005. When these events occurred, the protection schemes did not "see" nor isolate the condition, as this was discovered to be a design vulnerability. This was due to oversight in the design of the protection to detect this condition. This dissertation seeks to answer the following research question: **Is it possible to prevent or mitigate an open phase condition from occurring in the switchyard of a nuclear power plant?**

Previous work has attempted to address the lack of awareness of people working in close proximity to a Nuclear power station i.e. amongst staff working in the switchyard and operators in a nuclear plant, by sharing the operating experience (OE) of OPC occurrences. The approach to answer the research question lies in the analysis of the awareness of the people involved, as the condition cannot be prevented if it is not known. Case studies of the documented OE were categorised and analysed using a simplified root cause analysis method. A survey was conducted to assess the OPC awareness and perceptions of people in the system operator, i.e. TX division and at the Koeberg nuclear power station, within the Eskom Holdings utility.

The results demonstrate that there is insufficient overall knowledge and understanding of this condition within the system operator. Operators in the nuclear plants all over the world have been required by the US Nuclear regulator, to be trained and to be aware of this condition. The results of this dissertation highlight the focus areas in people's awareness that need attention. And that educating the system operator through training will strengthen the relationship between transmission and the nuclear plant within Eskom holdings.

Key words: Open Phase Condition, Operating Experience, Detection, Protection, Nuclear power plants

Contents

ABBREVIATIONS

AC	–	Alternating current
AF	–	Auxiliary Feedwater
AIS	–	Air Insulated Switchgear
AO	–	Auxiliary operator
AOO	–	Anticipated Operational Occurrences
AOT	–	Allowed Out of service Time
ARC	–	Auto Reclose
BB	–	Busbar
BS	–	Bus Section
BTP	–	Branch Technical Position
BU	–	Backup
CANDU	–	Canada Deuterium Uranium
CC	–	Component cooling water
CCDP	–	Conditional Core Damage Probability
CFR	–	Code of Federal Regulations
CTVT	–	Current transformer/ voltage transformer
CV	–	Centrifugal charging
DX	–	Distribution
ECWR	–	Essential Cooling Water Recirculation
ECCS	–	Emergency Core Cooling System
EDGs	–	Emergency Diesel Generators
EMTP	–	Electro-Magnetic Transient Program
EPRI	–	Electric Power Research Institute
ESF	–	Engineered Safety Feature
FENCO	–	First Energy Nuclear Operating Company
FW	–	Feedwater
GX	–	Generation
GDC	–	General Design Criterion
GIS	–	Gas Insulated Switchgear
GST	–	Generator Service Transformer
HIROP	–	High Resistance Open Phase
HV	–	High Voltage
H&V	–	Heating and Ventilation
IAEA	–	International Atomic Energy Agency
IEEE	–	Institute of Electrical & Electronics Engineers
IN	–	Information Notice
INPO	–	Institute of Nuclear Power Operations
IOS	–	Interruption of supply
KAS	–	Koeberg Auto Start
LCO	–	Limiting Condition of Operation
LCMP	–	Life Cycle Management Plan
LER	–	Licensee Event Report
LOOP	–	Loss of Offsite Power
LV	–	Low Voltage
MCS	–	Maintenance Cooling System
MT	–	Main Transformer
NEI	–	Nuclear Energy Institute
NG	–	National Grid
NOUE	–	Notice of Unusual Event

NPP	–	Nuclear Power Plant
NPS	–	Negative Phase Sequence
NRC	–	Nuclear Regulatory Commission
NSR	–	Non-Safety Related
OE	–	Operating Experience
OEM	–	Original Equipment Manufacturer
OOS	–	Out of Service
OPC	–	Open Phase Condition
OPD	–	Open Phase Detection
OSSO	–	Operations Shift Standing Order
PORV	–	Power Operated Relief Valve
RAI	–	Request for Additional Information
RCPs	–	Reactor Coolant Pumps
RHR	–	Residual Heat Removal
RSST	–	Reserve Station Service Transformer
SAT	–	Station Auxiliary Transformer
SF_6	–	Sulphur Hexafluoride
SIT	–	Special Inspection Team
S/Gs	–	Steam Generators
SOER	–	Significant Operating Experience Report
SOG	–	System Operating Guideline
SR	–	Safety Related
SRO	–	senior reactor operator
SRP	–	Standard Review Plan
SSCs	–	Structures, Systems and Components
SST	–	System Service Transformer
SSST	–	System Station Service Transformer
ST	–	Surveillance test
SX	–	Service water
TAR	–	Reserve Auxiliary Transformer
Tr	–	Transformer
TS	–	Technical Specification
TSSR	–	Technical Specification Surveillance Requirement
TX	–	Transmission
UAT	–	Unit Auxiliary Transformer
UST	–	Unit System Transformer
WANO	–	World Association of Nuclear Operators

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CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

According to the Nuclear Energy Institute (NEI) world statistics, there are 449 nuclear reactors installed in 30 countries all around the world, with an additional 60 nuclear plants under construction, as of April 2017 [1]. Safety in a Nuclear Power Plant (NPP) is of utmost importance, as the implications of a nuclear event have dire consequences on people, animals, and the environment and on unborn generations yet to come.

In the International Atomic Energy Agency (IAEA) safety report [2], "Impact of Open Phase Conditions (OPCs) on Electrical Power Systems of Nuclear Power Plants", the IAEA defines an Open Phase Condition as a condition when one or two of the three electrical phases of any electrical circuit of an electric system, is open circuited.

Up to 16 cases of the OPCs have occurred in different countries worldwide from 1994 till 2015. Safety is of utmost importance, hence sharing the operating experience (OE) is very crucial in the nuclear industry, as the shared information can prevent a similar incident from occurring elsewhere in the plant or in the world. Sharing of operating experience forms part of the safety culture that can be found in a NPP.

The open phase condition could occur in the transmission (TX) switchyard or on the High voltage (HV) side of the connected transformers or at the generator of the nuclear power plant, anywhere where there are three electrical phases; and during lightly (unloaded) or heavily loaded operating conditions. In previous occurrences, the protection schemes did not "see" nor isolate the condition appropriately, due to the design vulnerability that exists in the protection schemes in the NPP. This was due to oversight during the design process of the protection scheme, which omitted the detection of this condition. A single open circuit was not considered during the design process. Hence, an OPC has existed for long durations of time without being noticed by the operators or instrumentation, due to induced voltages from the other phases and possible parallel paths.

A condition or defect that exists in the plant, but is unknown, is worse than an existing condition or defect that is known.

1.2 RESEARCH OBJECTIVES AND MAIN QUESTION

The aim of the dissertation is to determine, if there is sufficient awareness of this Open Phase Condition (OPC) phenomenon as well as what an OPC is, how and why it occurs, what are the effects of an OPC, where it has occurred before, what happened, what was the operator's response and what is the current detection methods used. This will provide a broad understanding on the topic of open phase condition.

The main objectives of this research are to:

- Examine the available International operating experience using case studies and root cause analysis.
- Analyse the knowledge of staff working in the system operator within Eskom utility based on the results of a survey.
- Investigate the current OPC detection and mitigation methods.

The main research question of this dissertation is to investigate: **If it is possible to prevent or mitigate an Open phase condition (OPC) from occurring in the switchyard of a nuclear power plant?**

1.3 RESEARCH IMPORTANCE

The Open phase condition topic is important, as it can affect important systems, such as the offsite supply, protection systems, safe shutdown systems, electrical grid network, etc. in a nuclear power plant. This phenomenon has occurred in many NPPs around the world, including the Koeberg Nuclear Power Station (KNPS) in South Africa on the 11th November 2005. Hence, from past events there has been international operating experience (OE) on this subject to make nuclear operators aware and be better prepared for this phenomenon.

The majority of the NPPs do not have adequate protection devices installed to notify operators when an OPC is present. Namely an indication that one or two of the three electrical phases are not available; hence they do not respond appropriately or timeously [2]. The lack of adequate protection is due to a design vulnerability which was not addressed when the protection systems were originally designed. This condition has the capability to prevent important-to-safety equipment from operating when needed.

There is a need for system operators to be sufficiently aware of this phenomenon. Awareness of the OPC in TX is important, as the majority of the events take place in the switchyard of the NPP, which is deemed part of the TX network. Awareness of staff at the nuclear plant is important, as each reactor unit and the corresponding safety systems will eventually respond to an OPC. The effects of the OPC might reach the nuclear reactor unit and safe shutdown will be required. This could result in blackouts, due to insufficient generation available to the grid.

1.4 RESEARCH METHODOLOGY

A qualitative research method will be used to perform case studies, which will review related international operating experience and investigate whether it is possible to prevent or mitigate an open phase condition from occurring in the transmission switchyard. The operating experience gained from previous Open Phase events will be categorised. A case study on one event in each category will be analysed; giving a background of what happened and what was done to respond to the condition. A simplified Root cause analysis [3] was performed on the information available.

To collect the qualitative data, a survey was conducted as field research, to assess the awareness of OPC. The population of 150 people was requested within Eskom Holdings, System operator i.e. Transmission (TX) and Nuclear Generation (GX) divisions, to complete the survey. They were selected solely based on their working connection to either TX substations and/or the Koeberg NPP. A sample size of 30 % is expected for the response of the survey, which will provide a 95 % confidence level; this is explained in section 5.2.

The research survey consists of a short questionnaire of twenty (20) questions which will take each participant a maximum of 10 minutes to complete. The survey has four sections, i.e. A: Personal information, B: OPC awareness, C: Design vulnerability and D: International operating experience, with 4, 3, 6 and 7 questions in each section respectively. A mixture of partial agreement and descriptive open format questions were used, in order to allow the participant to share their valuable experience and knowledge on the topic.

These methodologies were chosen, as they achieve the research objectives and will give TX substation operators, nuclear operators and designers a better understanding of the effects of OPCs, how it can be mitigated and the root causes can subsequently be better understood. It will still remain the responsibility of the operators of the individual NPP and/or connected TX substations, to assess their plant and procedures continually, to ascertain if their plant is vulnerable to a possible OPC.

1.5 RESEARCH SCOPE AND LIMITATIONS

This research will be limited to the scope outlined in this dissertation, which will include the effects of the OPC which occurs on the transformer high voltage (HV) side. The focus of this dissertation is the analysis of the operating experiences based on the case studies and the survey analysis.

No simulations were done during this investigation. The actual plant simulations and modelling will not be covered, as each nuclear power plant has a different network configuration and layout. The various protection schemes and settings will also not be analysed, as this is plant specific. If these specific details were made available by the respective NPPs, the modelling and simulations could be used for further studies on this diverse and complex topic.

1.6 RESEARCH LAYOUT

This dissertation is organised using the following main headings:

- Chapter 2 provides a review of the literature on this topic that is relevant to this dissertation.
- Chapter 3 discusses the documented past events. These have been categorised in Table 3-1. One case study per category is analysed in more detail. Additional case studies can be found in Appendix A2.
- Chapter 4 analyses the OPC event that took place in the Koeberg Nuclear Power Station in South Africa.
- Chapter 5 provides evaluated results for the Eskom System operator staff awareness survey.
- Chapter 6 outlines the detection and mitigation methods currently available and in use at NPPs.
- Chapter 7 is the conclusion and recommendations of this investigation.
- Chapter 8 is the references utilised in this dissertation.
- The last chapter is the list of Appendices containing additional information.

CHAPTER 2 LITERATURE REVIEW

This chapter includes a review of the relevant literature covering the following aspects, namely the background of the topic, definitions of the open phase condition which occurs as a single or double type, the resulting effects and symptoms, the discovered design vulnerability, a review of the documents issued by Regulatory bodies, operator's response to the OPC, what models other authors have implemented to study this topic, as well as the various transformer configurations which could be affected.

2.1 INTRODUCTION

The electrical network is designed in such a way, that the protective systems should separate the defective section which had faulted, from the healthy sections of the network. Major considerations, when designing a power system should be "*determination and adequate protection against short circuits*" [4] . A short circuit that occurs in the circuits of the HV equipment could also be the cause that an OPC occurs.

The consequences of unattended and uncontrolled short circuits amongst others include [4]:

- Severe outages
- Damage to equipment
- Interruption of essential emergency systems
- Possible injury to staff

In an electric power system there are four basic sources that are the main contributors to short circuit faults [4]. These are generators, induction motors, synchronous motors and the Electric transmission systems. Open phase faults in the transmission system, which includes the nuclear plant's connecting switchyard, will be the area of focus. The occurrence of an open phase condition is critical; as it in most cases affects the loss of the offsite supply to the nuclear power plant, and this represents a "Significant Safety Event" [5]. The offsite supply should be a reliable source of power to the nuclear plant that is not located on the same site as the NPP. This includes the grid, the main generator and the equipment that links it to the busses of the nuclear plant [6]. According to Institute of Electrical & Electronic Engineers (IEEE) standard 308-1971 [7], the Offsite power source outlined in orange is the "preferred power supply" (see Figure 2-1), as it links the offsite supply to the Class 1E equipment (or power system) which is the safety related equipment at the nuclear plant.

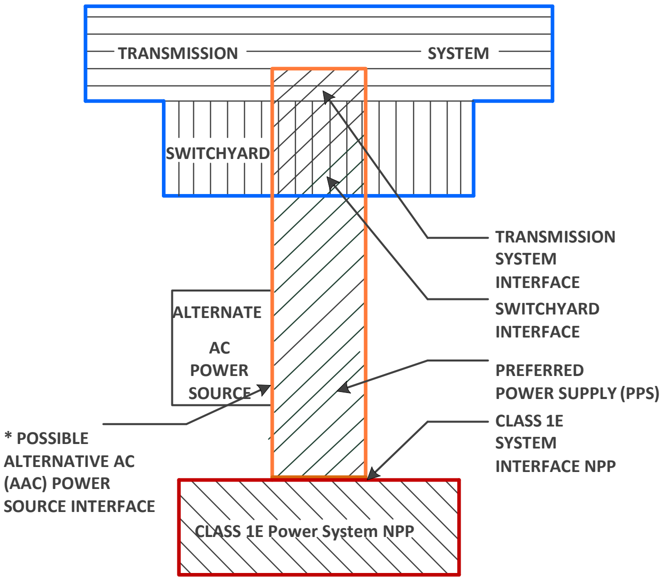


Figure 2-1 Typical station layout-preferred offsite supply [5]

2.2 BACKGROUND

There are three electrical phases that supply a power circuit for normal operation in a nuclear power plant (NPP) as well as the components for safety and non-safety systems. An Open Phase Condition (OPC) is defined as one or two of the three phases being unavailable. When one of the phases is "open", equipment that require a three-phase supply, get damaged and safety equipment is compromised [8]. An OPC can occur under various loads and in most system configurations, i.e. with or without a ground connection, on the High Voltage (HV) or Low Voltage (LV) side of the transformer.

When switching takes place and there are phase imbalances due to transients, it is not considered to be an OPC. These transients occur when there is opening, closing of circuit breakers and when auto reclose (ARC) protection operates to clear a fault on the overhead transmission (TX) lines. An earth fault with high impedance can occur along with an OPC, but it is not always the case.

2.2.1 SINGLE OPEN PHASE

According to [9] a single OPC is the *"Loss of one of the three phases of any power circuit required for normal operation, startup or shut down of a NPP or safe shutdown of a nuclear plant after an accident. An OPC can occur with or without a high impedance earth fault condition under all operating electrical system configurations and loading conditions."* [9] The OPC can be depicted by a 3-phase system with one phase e.g. Phase 'a', open between points x and x'. The boundary conditions are: $\Delta U_b = \Delta U_c = 0$ and $I_a = 0$ [2] (see Figure 2-2).

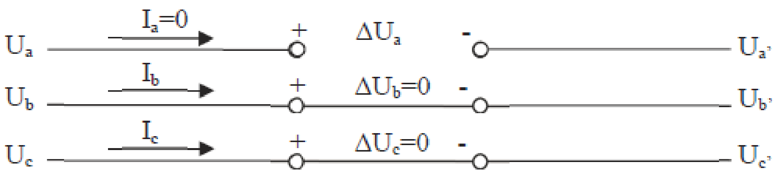


Figure 2-2 Generic 3-phase system with a single OPC

A single OPC can occur due to either:

- Broken insulators
- Broken phase conductors
- Opening or closing of only one circuit breaker
- Loose connections in the equipment's terminal box

2.2.2 DOUBLE OPEN PHASE

According to [9] a double OPC is defined the same as a single open phase, but here two phases of the power circuit is lost instead of one phase.

A double OPC can occur due to two broken phase conductors or two broken insulators or the opening/closing of two breakers, which are on two different phases. The OPC can be depicted by a 3-phase system with phases 'b' and 'c' open between points x and x'. For the double OPC on phases 'b' and 'c', the boundary conditions are: $\Delta U_a = 0$, $I_b = I_c = 0$ [2] (see Figure 2-3).

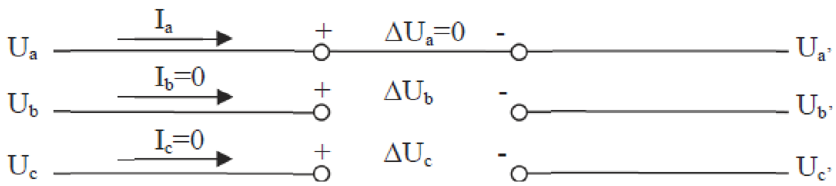


Figure 2-3 Generic 3-phase system with a double OPC

2.3 OPC EFFECTS AND SYMPTOMS

The effects of an OPC on a NPP can be devastating. The OPC effects depend on the location and duration of the unbalanced voltage. The loss of one phase of the offsite supply can potentially damage more than one of the emergency core cooling system (ECCS) trains [4]. This occurs when the train is supplied by the same source of power i.e. then it is called a "common cause failure". It is expected of the protection scheme to trip in order to separate the healthy section from the degraded supply system and switch to the emergency safety supply.

When an OPC occurs the "lost" voltage can be regenerated by induced voltages depending on the following [2]:

- Type of HV, LV windings (tertiary where applicable) of the transformer e.g. Star or Delta winding.
- Transformer's rated power and configuration of the core e.g. three or five legged, etc.
- The earthing layout of the system.
- The types and sizes of the loads being supplied by the transformer.
- Capacitances and inductances of overhead lines or underground cables.
- The place where the OPC occurs.

An OPC causes negative sequence voltage and current unbalance in the Alternating Current (AC) system [10]. If an OPC occurs and it is not detected timeously, the unbalanced voltage could lead to the following effects, with the associated symptoms (see Table 2-1):

Table 2-1 Open phase condition effects and symptoms

Effects	Symptoms
Running motors could overheat	Increased heat and sound level
Rotating machines could get damaged	Unbalanced voltage and current
Protection equipment trip and lock out	Motors would trip after start-up
Excessive vibration	Vibration
Unintended tripping of electrical plant	Tripping various other equipment
Plant transients	Alarms will be triggered

If an OPC occurs in a circuit that is not loaded or is lightly loaded, the unbalanced current magnitude might not be sufficient to trip protection relays. In most cases the OPC can go undetected, until any of the following occurs [2]:

- Loading conditions change by connecting or disconnecting load
- Transmission network is reconfigured by operating breakers
- A line fault occurs and loads trip

When an OPC event occurs, zero sequence currents will be present in the transformers' primary terminals [11]. Due to the load's neutral connection, the resultant zero sequence current in the transformer's secondaries will be zero. When an OPC occurs on the HV side of the generator transformer, the downstream voltages may all still be available. During lightly loaded or no load conditions, the LV side of the transformer may still show balanced voltages [2].

2.4 DESIGN VULNERABILITY

Design vulnerability is as the Institute of Nuclear Power Operations (INPO) stated that the original protection design and licensing bases did not anticipate a single-phase failure to the system auxiliary transformers (SAT). Thus, the under-voltage and overcurrent protective functions associated with the safety buses and the SAT were not designed to detect such a failure [12].

The design vulnerability in NPPs was brought to light when an Open phase condition occurred at Byron Unit 2 Nuclear plant on the 30th January 2012. The reactor was operating at full power when two ('B' and 'C') out of the four reactor coolant pumps (RCPs) tripped and sent a reactor trip signal, due to an under-voltage state on the 6.9 kV buses [4]. The under-voltage was due to a broken 345 kV insulator on the 'C' phase that supplies the station's auxiliary transformers. The protection relays in the switchyard did not sense the open circuit on phase 'C' and hence did not operate. This failure in the design to sense the loss of an electrical phase between the TX network and onsite system caused unbalanced voltage on the engineered safety feature (ESF) buses [4]. This event will be looked at in more detail later in the Case studies, see chapter 3.3.1.

The design vulnerability in NPPs' control rooms exists as the installed instrumentation that is used for measurements, alarms and indications do not provide the correct or adequate information regarding the existence of an OPC. Hence, the protection scheme does not automatically trip to separate the faulty portion of the system from the healthy portion. Operators then had to manually intervene, after correctly diagnosing the symptoms. The OPC event that occurred in the Byron NPP in 2012 was a turning point and caused a ripple effect in the nuclear industry.

2.5 REGULATORY BODIES

Due to the occurrences of the Open phase conditions through the years, the nuclear industry responded by issuing Licensee Event Reports (LERs), Information notices (INs), bulletins, etc. These communications were issued to create awareness of this phenomenon. These responses are outlined as follows:

2.5.1 U.S. NRC

The United States Nuclear Regulatory Commission (U.S. NRC) took action by requesting that all licensees provide their short- and long-term action plans on how they will address the protection design features that will "sense" when an OPC occurs and initiate signals for the correct relays to isolate the faulted section. The protective scheme's correct response will ensure that the offsite and onsite power systems have adequate ability to be immediately available, to permit functioning for structures, systems and components (SSCs) that is important for safety in the event of an Anticipated Operational Occurrence (AOO) [4].

The U.S. NRC issued the following communications:

- **Information Notice** (IN) 2012-03: "Design Vulnerability in Electric Power System" [13]

The IN 2012-03 creates awareness amongst licensees of the operational experience at Byron NPP, as well as other applicable OE.

- **Bulletin** 2012-01: "Design Vulnerability in Electric Power System" [14]

This Bulletin requires licensees to respond, by giving confirmation of their compliance to Title 10 of the Code of Federal Regulations (10 CFR) Part 50 which is the "Domestic Licensing of Production and Utilisation Facilities". Specifically, their compliance to design criteria for protection systems in 10 CFR 50.55a(h)(2), 10 CFR 50.55a(h)(3) and General Design Criterion (GDC)17- "Electric Power Systems". NRC requested information about the design of the electrical system at each nuclear facility.

- **Standard Review Plan** (SRP), NUREG-0800 [15]

The SRP is a plan that gives criteria to be used by the staff of the U.S. NRC. These criteria are used to review the applications of licensees and/or new applicants who want to construct and operate a NPP, to ascertain if the applicant meets the regulations. Compliance to the SRP is not mandatory, as it is not a substitute for the regulations of the NRC. It is the responsibility of the applicant to identify the differences between the design features, analytical techniques and procedural measures proposed which are applicable to their station. The SRP provides the acceptance criteria and evaluates how the suggested changes can provide an acceptable method for compliance.

- **Branch Technical Position** (BTP) 8-9: "Open Phase Conditions in Electric Power systems" [15]

The BTP 8-9 sets out the guidelines and design criteria that should be used by the staff of the NRC. The guidelines and criteria will be used when actions regarding the OPC design vulnerability require reviewing and for future license applications.

- **Summary report** was issued by the NRC on the 26 February 2013 [16]

The summary report gives a full account of what happened at the OPC events that occurred at Byron NPP on the 30th January 2012 and 28th February 2012. They also analyse the responses received from the licensees.

- On the 20th December 2013, the U.S. NRC sent out a **Request** for **Additional Information** (RAI) [17] from all nuclear operators.

The RAI request covered the following:

- Licensees had to summarise the temporary corrective actions that have been taken since 30th January 2012 and what compensatory measures were implemented regarding operator's awareness to diagnose and correctly respond to the condition.
- Each licensee had to indicate the status of the long-term corrective actions identified, such as possible modifications to be implemented.

The regulatory obligation as per the NRC GDC 17 states the requirements for NPPs' electrical design. The requirements are as follows (emphasis added):

*"An **onsite** electric power system and an **offsite** electric **power system** shall be provided to permit functioning of SSC's important to safety. The safety function for each system (assuming the other system is not functioning) shall be to **provide sufficient capacity and capability** to assure that (1) specified acceptable fuel design limits and design conditions of the reactor coolant pressure boundary **are not exceeded as a result of anticipated operational occurrences** and (2) the **core is cooled and containment integrity** and other vital functions are **maintained in the event of postulated accidents**….*

*Electric power from the transmission network to the onsite electric distribution system shall be supplied by **two physically independent circuits** (not necessarily on separate rights of way) designed and located so as to minimize to the extent practical the likelihood of their simultaneous failure…." [17]*

2.5.2 INPO

The Institute of Nuclear Power Operations (INPO) issued event reports Level 2 12-14: "Automatic reactor scram resulting from a Design Vulnerability in the 4.16 kV bus under-voltage protection scheme." The notice was issued in February 2012 and shared the OPC OE that occurred at Byron Unit 2. It sets out guidelines for licensees to assess their nuclear plants [12]. Level 3 13-13 was also issued, to give a standard as there has not been a standardised process to analyse these types of faults.

2.5.3 NEI

The Nuclear Energy Institute (NEI) issued the NEI 13-12: "Open phase condition industry guidance" document. Their aim was to establish a task force that would take the lead regarding the investigation of the OPC and organised numerous workshops where interested and affected people could come together and learn from others' experiences.

2.6 OPERATORS RESPONSE

An OPC is now a more well-known phenomenon in the nuclear power industry, than it was less than five years ago, as the OE should be widely distributed after an event has occurred. When an OPC occurred prior to 2012, operators had to rely on what information was available and on their individual experience from operating in a nuclear power plant. Based on past events, operators took valuable time to assess the situation before a decision was made on what to do and this could have led to equipment damage. It is hence crucial that operators are regularly well trained to recognise the effects of an OPC and act promptly to reduce the effects on the plant.

2.7 MODELING

In the Electric Power Research Institute's (EPRI) 2012 [11], 2013 [19] and 2014 [20] Technical reports, the authors aim to address the technical issues that are experienced with detecting an OPC in a Station Auxiliary Transformer (SAT). In the technical reports, various transformer models were developed to analyse the response under various loads.

EPRI research shows that the system response to an OPC can be accurately simulated and the response mainly depends on the connection of the transformer windings and the configuration of the core [19]. Based on the literature on this topic, various authors used the following models for their analyses i.e. source models, transformer models and load models. These models are used to simulate the responses a three-phase transformer would have when an Open phase occurs. Using a simplified model and doing slight modifications to the connections of the transformer, voltages and loading levels; different scenarios were simulated in the EPRI reports. The simplified model can be seen in Figure 2-4, showing the source, transformer (Tr) with various connected loads and various earthing methods.

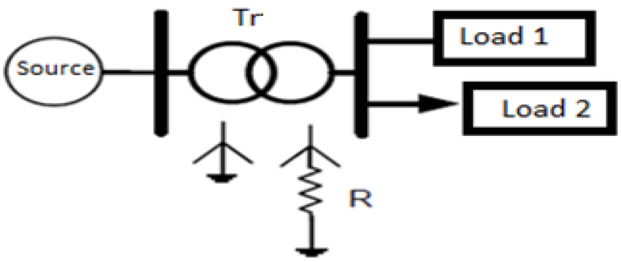


Figure 2-4 Single line diagram of simplified model [11]

According to the IAEA OPC safety report the following must be considered when doing simulation analysis [9]:

- **Plant status** - when to apply the OPC: All configurations and various loading conditions in all electrical systems must be analysed for all possible plant status.

- **Zone of study** - where to apply OPC: The zone is specific to the plant and all possible places that could affect safety should be studied.

- **Type of OPC** - what kind of OPC: OPC types are either single or double and can occur with or without a high impedance earth fault.

The IAEA safety report states that the unbalance withstand capability of the nuclear plant's electrical systems and safety equipment should be assessed. Depending on the site-specific simulation results, if the OPC has the potential to degrade the abilities of the safety systems, then the equipment should be upgraded to withstand the unbalance or appropriate protection must be installed to protect that equipment.

In EPRI's analysis of the response of SATs to an OPC, simulations in both the time and frequency domains were analysed [11]. EPRI-OpenDSS was used for the frequency domain and ElectroMagnetic Transients Program (EMTP-RV) was used for the time domain simulations. In their modelling:

- **Source models -** A simple Thevenin model was used to represent the source, with a balanced 3-phase voltage.
- **Transformer models -** Using the OpenDSS software, the windings of the transformer are displayed and coupled as a real transformer would be.
- **Load models -** To analyse the effects of OPC, both the static and dynamic load conditions were simulated. Static loads were presented as constant impedances with resistive values. Dynamic loads were presented as the inductive component, for induction machines.

The three-legged core transformer with two, three and four windings was simulated with various loads. The results from the analysis showed that the transformer response to an OPC depends on the configuration of the transformer. Under lightly loaded conditions, more zero sequence current (I_0) is produced and this zero sequence current should be used for primary current detection [11]. When the loading is increased, the negative sequence current (I_2) increases as well. Hence the negative sequence detection should be used for heavily loaded transformers [11]. The construction of the transformer also has a major effect on the presence of the negative sequence component.

A summary of the results of the EPRI OPC analysis with a small induction motor load less than 10 % of the transformer rating and a large induction motor load which is more than 74 % of the transformer rating is shown in Table 2-2 and Table 2-3, respectively [11]. After normalizing the zero (I_0) and negative (I_2) sequence current values with the positive sequence current (I_1) value, the results from the two software models were in the same value range, when simulating a single OPC. For the time domain simulations (EMTP) a damping resistance of 200 ohms was put in parallel with the short-circuit impedance. For the frequency domain simulations (OpenDSS) the short line segment was placed in series with the short circuit impedance [11].

Table 2-2 EPRI Results of OPC – Small induction motor load [11]

	OpenDSS		EMTP	
	(I_0/ I_1 %)	(I_2/ I_1 %)	(I_0/ I_1 %)	(I_2/ I_1 %)
Two-Winding Three-Legged Core Form (Transformer A)	92.4	10.8	90.3	12.6
Two-Winding Three-Legged Core Form (Transformer B)	75	23.9	75.2	25.7
Three-Winding Three-Legged Core Form Transformer	99	0	96.7	3.4
Four-Winding Three-Legged Core Form Transformer	86.2	13.8	89.7	10.3

Table 2-3 EPRI Results of OPC – Large induction motor load [11]

	OpenDSS		EMTP	
	(I_0/ I_1 %)	(I_2/ I_1 %)	(I_0/ I_1 %)	(I_2/ I_1 %)
Two-Winding Three-Legged Core Form (Transformer A)	52.7	47.7	51.4	49.3
Two-Winding Three-Legged Core Form (Transformer B)	34.7	65.3	31.8	68.9
Three-Winding Three-Legged Core Form Transformer	83.9	15	73.4	26.9
Four-Winding Three-Legged Core Form Transformer	49.6	50.4	52.1	48.5

The evaluation of an OPC is primarily focussed on quantifying the unbalanced voltages and currents, and the calculations and/or simulations used should encompass all possible configurations and loading conditions [2]. By modelling the network, the system response can be assessed. The results indicate that during lightly loaded conditions only monitoring the voltage will not identify all the OPCs and that current monitoring is also required [2] [11].

In [4] the authors use the short circuit analysis method by implementing the bus impedance matrix to compute the unbalanced voltages and currents [4]. They use symmetrical components to simplify the modelling of such complex faults.

The authors also feel there is a need for detailed models that specify the following:

- Motor models
- Transformer magnetic circuit models
- Models of the electrical distribution system
- Analysis of the Class 1E plant specific electric system details
- The zero, positive and negative sequence impedances, voltages and currents

According to the simulations below which were done by the IAEA [2], they found the following results after simulating a single OPC. The event was simulated on a 400 kV line connecting to the nuclear plant's three-legged core unit transformer. The event was initiated after 0.2 seconds. The Figure 2-5 and Figure 2-6 show the sinusoidal phase voltage and vector diagram of each phase before and after the event. Va(t) is red, Vb(t) is green and Vc(t) is blue indicate the 3 voltage phases. These voltages were recorded on the HV side of the transformer. Their results reveal that existing instrumentation in nuclear plants are not adequate to indicate when an OPC has occurred, as can be seen in the phase voltages. These results show that there is no change in the voltages after an OPC has occurred.

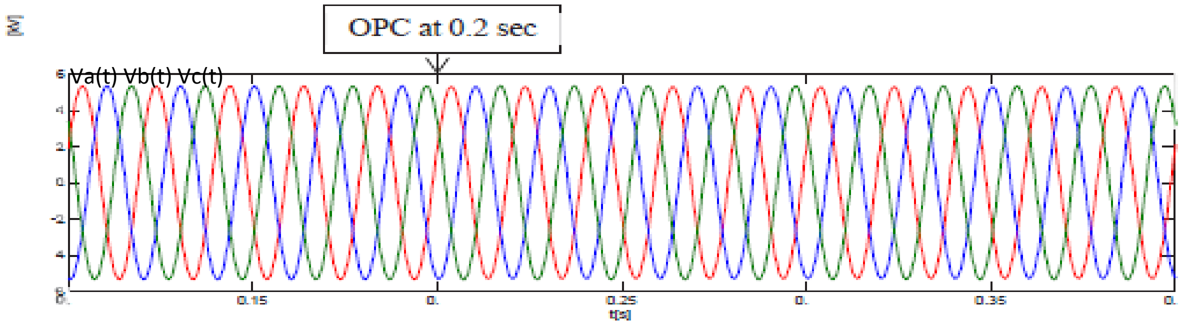


Figure 2-5 Single OPC in the 400 kV line to the Unit transformer [2]

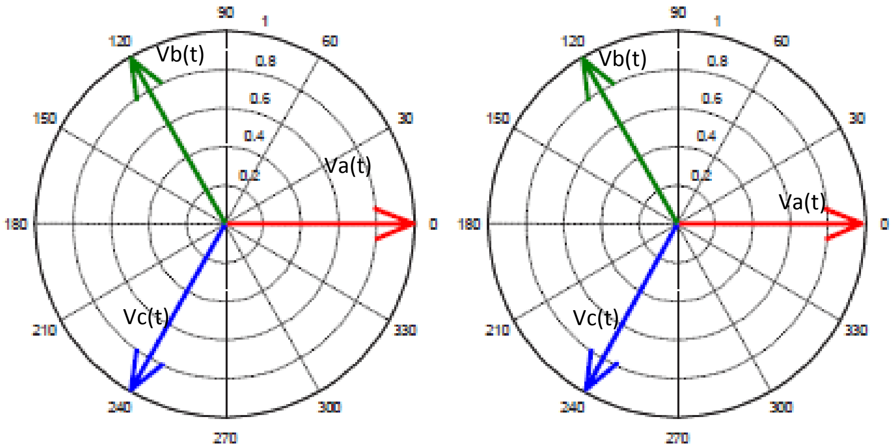


Figure 2-6 Vector diagram before (left) and after (right) the single OPC [2]

IAEA also simulated a double OPC and they found the results below, where the event was simulated with 2 phases ('B' and 'C' phase) open on a 400 kV breaker on the HV side of the unit transformer. The event was initiated after 0.2 seconds. The Figure 2-7 and Figure 2-8 show the sinusoidal phase voltage and vector diagram of each phase before and after the event. Their results showed that even with two open phases on the HV side, three-phase voltages can still be recorded on the LV side of the transformer, with decreased voltage magnitudes and unbalanced phases. It was stated that the results do depend on the transformer configuration.

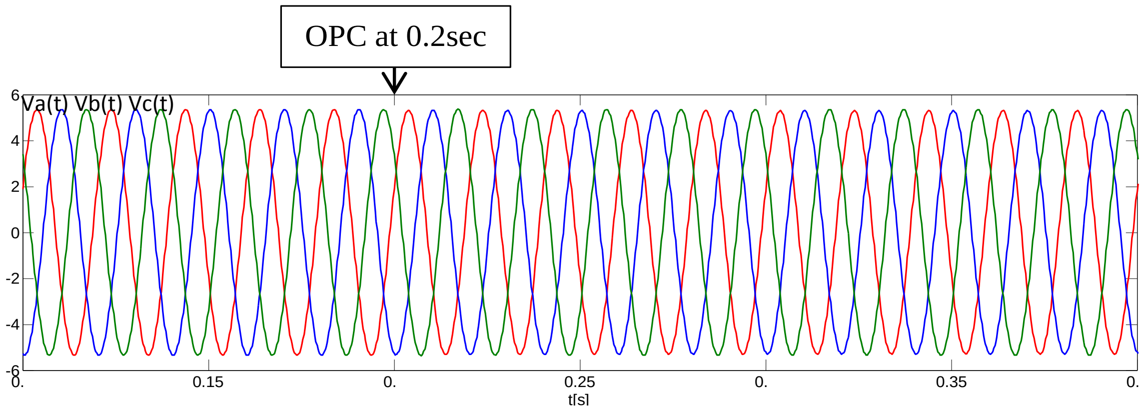


Figure 2-7 Double OPC in the 400 kV line to the Unit transformer [2]

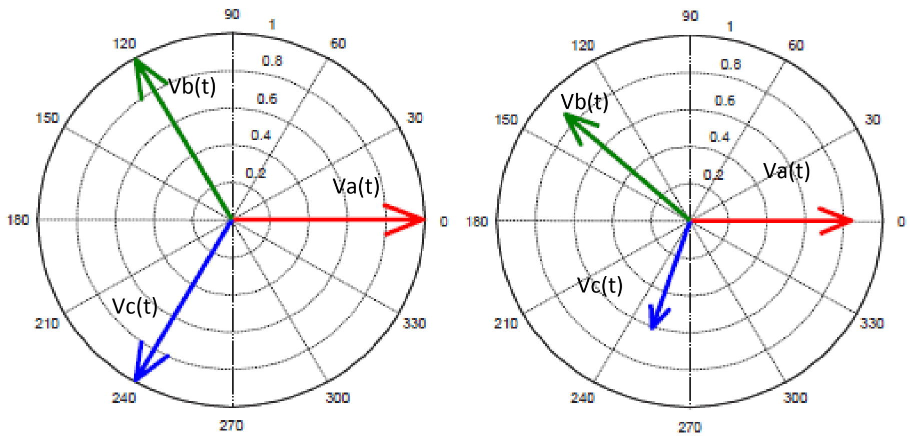


Figure 2-8 Vector diagram before (left) and after (right) the double OPC [2]

2.7.1 Yy0 TRANSFORMER

The Yy0 transformer with the HV side star point isolated was simulated; these are typically used as power transformers in substations. The following results were found by the IAEA (see Figure 2-9). The simulations were carried out on a three-legged core transformer with the single OPC occurring at 0.1 s which is indicated as 1OPC and double OPC taking place at 0.2 s which is indicated as 2OPC. The voltages from the HV side of the unloaded Yy0 transformer can be seen in Figure 2-9. After 1OPC, the red phase which was the open circuited phase decreased in magnitude and goes 180^0 out of phase (see Figure 2-9 middle). After 2OPC, all three HV phase-to-earth voltages have the same magnitude and angle (see Figure 2-9 right).

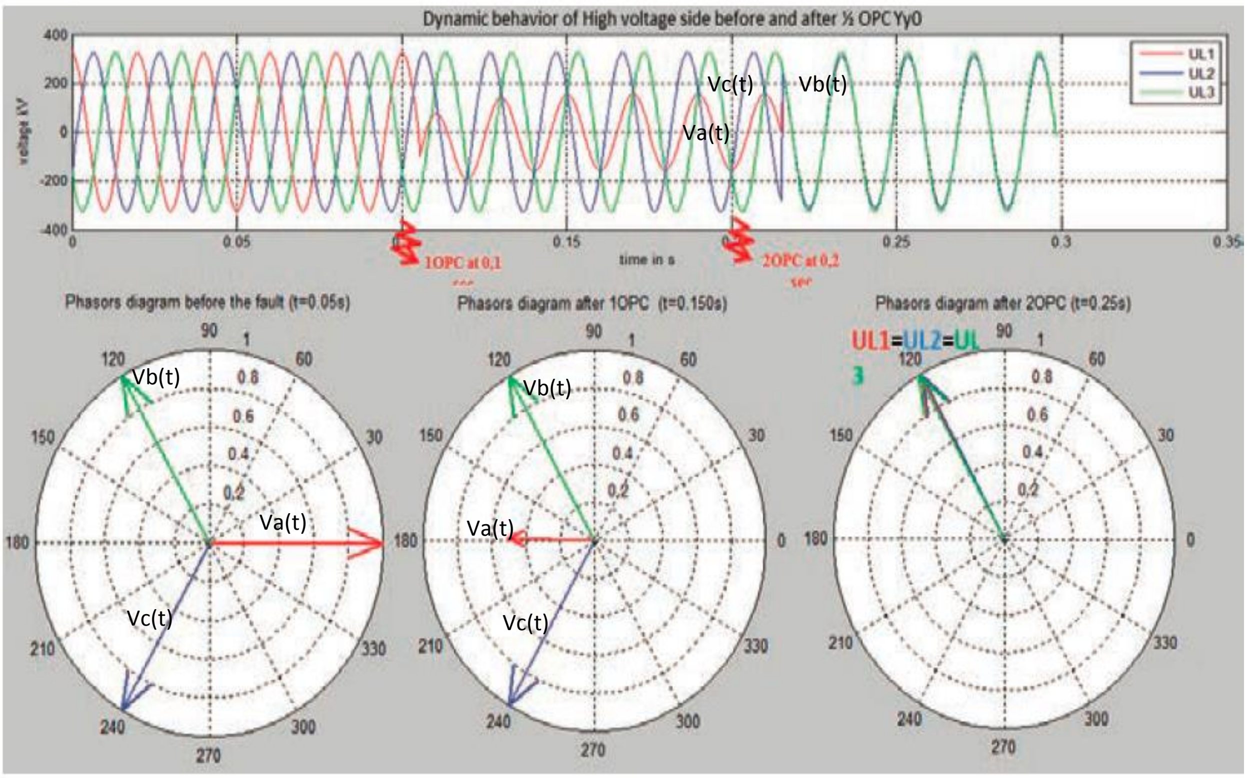


Figure 2-9 Before (left), After 1OPC (middle), After 2OPC (right) HV side of unloaded Yy0 Tr [2]

Simulating the same transformer under the same conditions as above, but this time the voltages from the low voltage (LV) side of the unloaded Yy0 transformer were monitored and can be seen in Figure 2-10. After 1OPC (see Figure 2-10 right), the red phase which was the open circuited phase decreases to zero and the other two LV phases decrease in magnitude and the phase angles change to 180^0 out of phase. After 2OPC, all three LV phase-to-earth voltages go to zero.

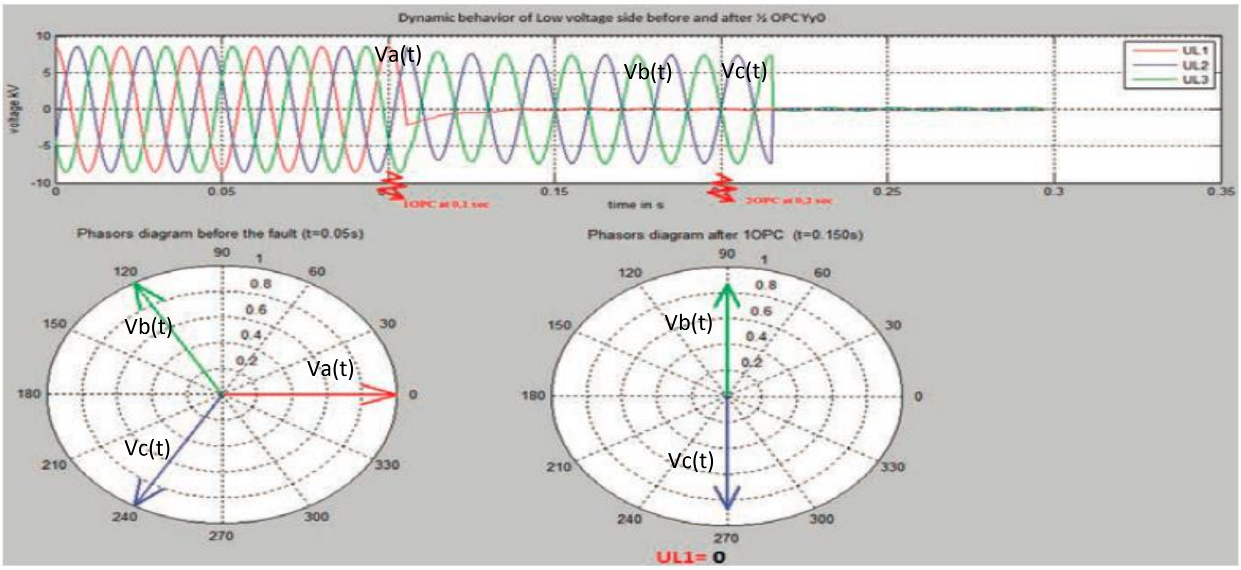


Figure 2-10 Before (left), After 1OPC (right) LV side of unloaded Yy0 Tr [2]

2.7.2 YNy0 TRANSFORMER

When the YNy0 transformer with the HV side star point solidly earthed was simulated, the following results were found by the IAEA. The simulations were carried out on a three-legged core transformer with the single OPC occurring at 0.1s which is indicated as 1OPC and double OPC taking place at 0.2 s which is indicated as 2OPC. The voltages from the HV side of the unloaded YNy0 transformer can be seen in Figure 2-11. After 1OPC (see Figure 2-11 middle), the magnitudes and angles remained the same. After 2OPC (see Figure 2-11 right), the two HV phase-to-earth voltages which were open circuited, i.e. red and blue phase had the same magnitude and angle. This is different from the previous transformer vector group.

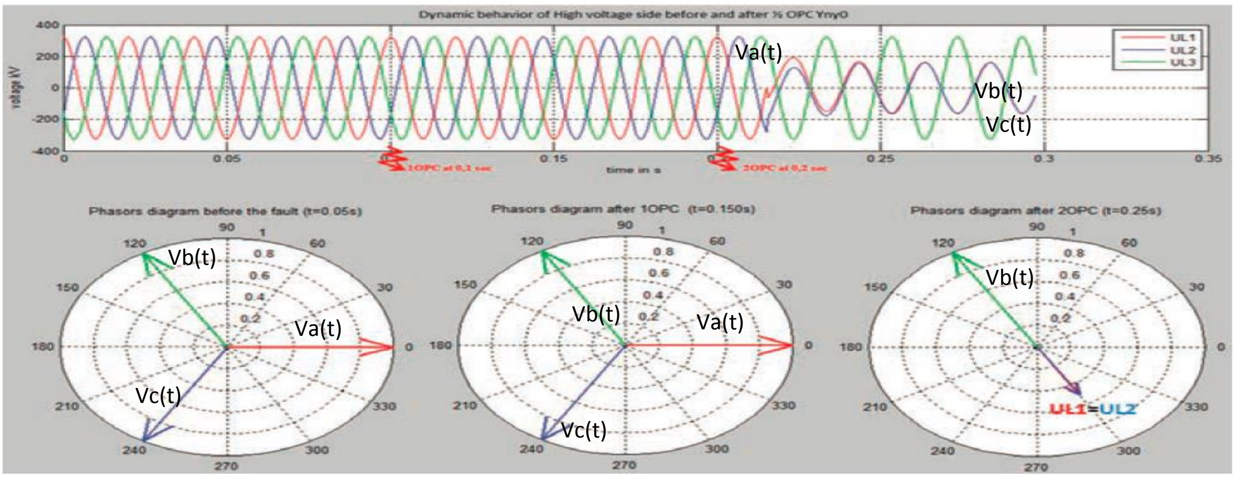


Figure 2-11 Before (left), After 1OPC (middle), After 2OPC (right) HV side of unloaded YNy0 Tr [2]

The results of the LV side of the YNy0 unloaded transformer are the same as on the HV side of the transformer.

2.8 TRANSFORMER CONFIGURATIONS

The unit transformer is usually a Star-Delta configuration [2]. Whether the star point of the transformer is solidly earthed or not earthed, this does have an effect on the transformers' response to an OPC.

According to the Technical reports entitled "Development and Analysis of an OPD scheme for Various Configurations of Auxiliary Transformers" [19] and "Development and Analysis of a Double Open-Phase Detection scheme for Various Configurations of Auxiliary Transformers" [20] the various SAT configurations were analysed and only the no load summary results are highlighted here in Table 2-4 for a single OPC and Table 2-5 for the double OPC. Each table shows the line to neutral (V_{LN}) per unit voltage for the primary and secondary side of each transformer configuration, which is highlighted in the same colour for ease of reference. For the single OPC - phase 'A' was open circuited and for the double OPC - phases 'A' and 'B' were open circuited. The transformers were implemented as step down transformers. All the transformer configurations can be seen in Appendix A1.

Table 2-4 Prim and Sec V_{LN} single OPC phase 'A' – no load [19]

	Primary Voltage (pu)			Secondary Voltage (pu)		
PHASE	A	B	C	A	B	C
Star - Star: shell core	0	1	1	0	1	1
Star - Star: 5-legged core	0.54	1	1	0.54	1	1
Delta - Star: 3-legged core	0.5	1	1	0.5	1	0.5
Star - Delta: 3-legged core	1	1	1	1	1	1
Star - Delta - Star: shell, buried Delta	1	1	1	1	1	1

Table 2-5 Prim and Sec V_{LN} double OPC phase 'A' & 'B' – no load [20]

	Primary Voltage (pu)			Secondary Voltage (pu)		
PHASE	A	B	C	A	B	C
Star - Star: shell core	0	0	1	0	0	1
Star - Star: 5-legged core	0	0.44	1	0	0.44	1
Delta - Star: 3-legged core	1	1	1	0	0	0
Star - Star: 3-legged core	0.5	0.5	0.99	0.5	0.5	0.99
Star - Delta: 3-legged core	0.5	0.5	0.99	0.86	0	0.86
Star - Delta - Star: shell, buried Delta	0.5	0.5	0.99	0.5	0.5	0.99

According to EPRI, for unloaded transformers the response to the open phase, is that the voltage on the "*transformers' open phase (phase 'A') falls to or below approximately 50 %"* when comparing the secondary per unit voltage of a single OPC with a double OPC of the same transformer configuration. *"The exception of the Star-Delta and Star-Delta-Star shell with the buried delta tertiary, both of which behave like a three-legged Star-Star core form."* [11] [19] *"During a single open phase condition these configurations are also able to recreate the open phase voltage."* [20]

The EPRI 2014 report found that any transformer with a delta primary winding would trip during a double OPC, hence the Delta – Star 3- legged core transformer in Table 2-5 shows zero per unit values on all three secondary phases, as there will only be one closed phase, hence there is no possibility for a closed loop in the circuit for the current to flow in a delta configuration. With the Star – Delta winding 3-legged core this is not the case.

During simulations, with motors running and a double OPC occurring on the HV side of the transformer, only the following transformer designs can maintain the operation of the motors, i.e. Star-Delta, Star-Star with buried tertiary Delta and Star-Star 3-legged core configuration [20]. On the transformer secondaries there will be a low voltage condition during no-load conditions. A double OPC also inhibits motors from starting up again.

2.9 SUMMARY

Several studies have been published to address the Open phase condition phenomenon, and the topic is well defined. The US NRC and other nuclear organisations have issued several documents that aim to share the OE of the OPC at Byron NPP in 2012, in order for others to learn from their experiences.

Different models have been developed and studied to assess which transformer configuration is more susceptible to the OPC. It was found that the Star-Delta 3-legged core and Star-Delta-Star with the buried tertiary Delta, respond like a Star-Star 3-legged core configuration which recreates the open phase voltage, during a single OPC. Any transformer with a primary Delta winding in a double OPC event has no closed loop for current to flow and the transformer will trip.

The operators and licensees still have the responsibility to continually assess their own nuclear power plants and to address any design vulnerability issues that exist.

CHAPTER 3 CASE STUDIES

3.1 INTRODUCTION

To further analyse the literature on this topic, the Open phase events will be analysed on an individual basis, through case studies. There are sixteen (16) OPC occurrences world-wide from 1994 till 2015. The corrective actions taken at two of the nuclear power plants will be analysed.

Figure 3-1 shows the value and percentage of OPC occurrences and where the majority of the have taken place world-wide. The majority at six events which is 37 % of the total documented Open phase occurrences took place in the United States of America. This is due to them having the most nuclear power plants in the world [21].

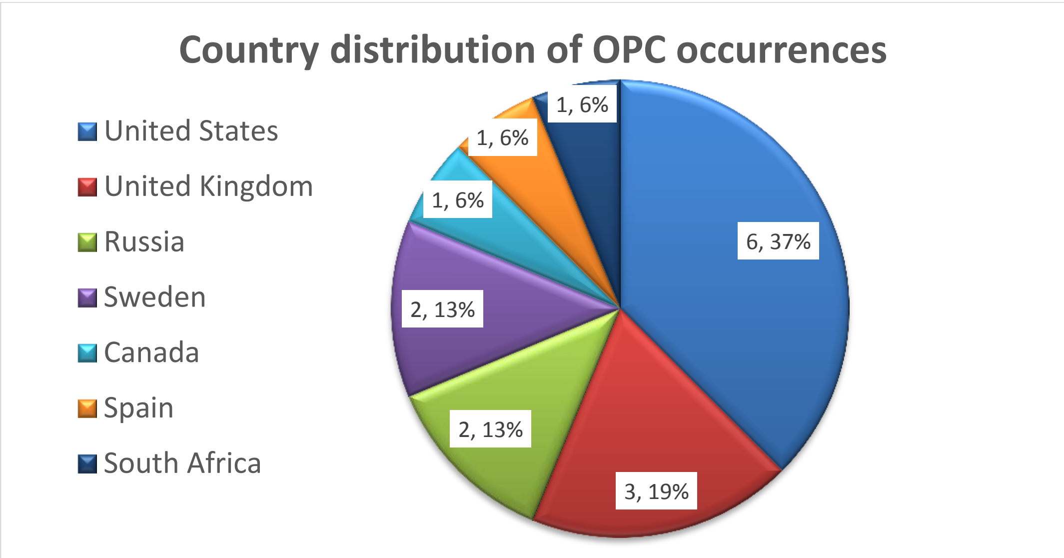


Figure 3-1 Pie diagram showing Country distribution of OPC occurrences

Figure 3-2 shows that most of the OPC events (10) occurred prior to the year 2012, with a spike of three events taking place in that year. After 2013 on average there was one event per year. This indicates that the awareness has led operators to being more proactive.

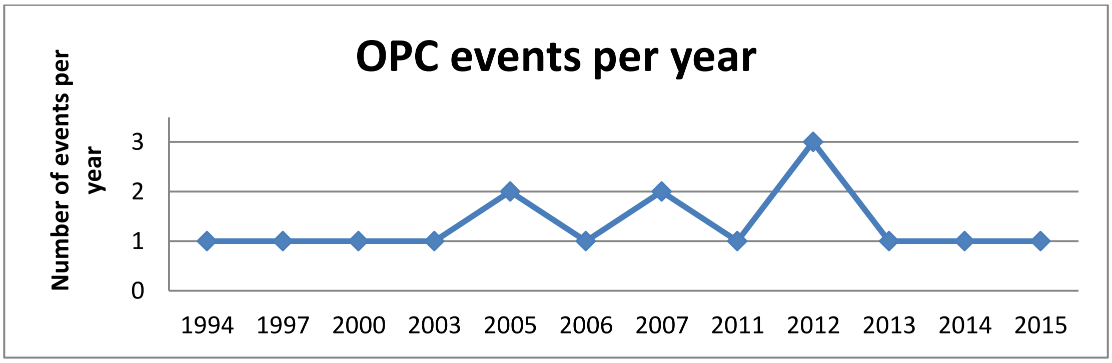


Figure 3-2 OPC events per year

3.2 OPC EVENTS CATERGORIES

The 16 listed OPC events have been categorised into four groups:

A. Material weakness:
   a. Insulators
   b. Conductors
B. Faulty equipment:
   a. Isolators
C. Switching or maintenance:
   a. Loose connections
   b. Breakers
D. Transformer connections

The 4 groups are based on the cause of the OPC. For simplicity, one case will be analysed in each category, based on the available information. Each case study sets out the following subheadings: “Station Layout” of the specific NPP showing the reactor unit(s), transformers, generators, safety buses and the connecting voltage switchyards, “Event Details” which gives the background and details of the event and then the “Cause of OPC” is analysed using the simplified “WHY” method to determine the root cause. A short summary of the additional OPC events are mentioned at the end of each category and the full case study’s details can be found in the appendix A2.

- Category A is the “Material Weakness” of the equipment i.e. insulators, conductors. This group refers to where the equipment has failed due internal manufacturing defects.
- Category B is “Faulty Equipment” which covers isolators and the cause of the OPC is due to external factors, i.e. mechanical loading, etc.
- Category C is when an OPC occurs due to loose connections in the secondary circuits or breakers not making proper contact and it is revealed due to the “Switching or Maintenance” that took place.
- Category D is “Transformer connections” which is a group that covers OPCs that occur due to cable connections breaking off at the transformer.

Table 3-1 lists the recorded cases and the category. Three of the OPC events were recorded, but insufficient information was found and therefore was excluded from the case studies. These were Heysham station, South Texas project and Ringhals station.

Table 3-1 16 Open Phase Condition events summary from 1994-2015

#	Date	NPP	Unit	Country	Event description	Catergory
1	13/05/1994	Kalinin station	1	Russia	750 kV phase ‘B’ cable broke off on autotransformer clamp, got damaged due to fatigue induced fracture of aluminium plate	Transformer connections
2	25/02/1997	Balakovo station	1, 3	Russia	220 kV phase ‘A’ breaker on main Tr erroneously closed due to open circuit in breaker contact	Switching or maintenance: Breakers
3	30/12/2000	Heysham station	2	United Kingdom	OPC in a 400 kV TX circuit breaker resulted in a manual reactor trip. The condition was undetected for approx. 2 hours.	Switching or maintenance: Breakers

4	19/01/2003	South texas project	1	USA	A malfunctioning breaker in the switchyard created an OPC. Breaker pole in switchyard failed to close.	Switching or maintenance: Breakers
5	11/11/2005	Koeberg station	1	South Africa	400 kV red phase isolator drive shaft was displaced and did not close properly on 400 kV bus section 1A in the TX switchyard.	Faulty equipment: Isolators
6	19/12/2005	James A. Fitzpatrick Nine-Mile Point	1	USA	115 kV phase 'A' conductor broke off at busbar isolator in switchyard, due to mechanical overload	Faulty equipment: Isolators
7	09/09/2006	Vandellòs station	2	Spain	400 kV phase 'R' cable on support insulator broke off in the switchyard	Switching or maintenance: Loose connections
8	14/05/2007	Dungeness station	B	United Kingdom	One pole of the HV Tr breaker failed to close properly	Switching or maintenance: Breakers
9	27/11/2007	Beaver valley	1	USA	138 kV phase 'A' power line conductor was found broken. The SAT insulator failure went undetected for approx. 26 days.	Material weakness: Conductors
10	17/04/2011	Ringhals station	2	Sweden	One pole of the standby AC power source generator breaker did not work properly during a load run test.	Switching or maintenance: Breakers
11	30/01/2012	Byron station	2	Illinois, USA	345 kV phase 'C' broken underhung insulator stack on station auxiliary transformer caused a single OPC.	Material weakness: Insulators
12	28/02/2012	Byron station	1	Illinois, USA	345 kV phase 'A' broken underhung insulator stack on station auxiliary transformer caused a single OPC.	Material weakness: Insulators
13	22/12/2012	Bruce A station	1	Canada	230 kV side of the system service transformer jumper broke from the baseplate. Mechanical failure during severe weather	Material weakness: Conductors
14	30/05/2013	Forsmark station	3	Sweden	Human error and a loose cable resulted in a double OPC in the 400 kV breaker. The failure was not detected by the loss of voltage relays.	Switching or maintenance: Loose connections
15	27/04/2014	Dungeness station	B	United Kingdom	A single OPC in a 400 kV Open breaker pole in switchyard	Switching or maintenance: Breakers
16	07, 15/12/2015	Oconee station	1, 3	Seneca, USA	230 kV phase 'Y' bushing conductor to the startup transformer CT3 broke off	Transformer connections

3.3 MATERIAL WEAKNESS

3.3.1 INSULATORS

BYRON UNIT 2, ILLINOIS, USA, 30 JAN 2012

- ***STATION LAYOUT***

The Byron Nuclear Power Station (BNPS) is owned by Exelon and is situated in Northern Illinois, which is North-West of Chicago in the United States of America. The nuclear generation power station has two 4-loop Pressurised Water Reactor (PWR) units manufactured by Westinghouse; unit 2 is shown in Figure 3-3. Each unit consists of two non-safety 4.16 kilovolt (kV) buses, two engineered safety feature (ESF) 4.16 kV station buses and four non-safety 6.9 kV buses. The two 4.16 kV ESF buses are energised from either Station auxiliary transformer (SAT) 242-1 or 242-2 which is used for revenue metering [11]. There are dedicated emergency diesel generators (EDGs) for each 4.16 kV ESF bus. There are two SATs per reactor unit, which are connected to the 345 kV offsite switchyard, via a single Ring bus connection. The second offsite power source is supplied to the 4.16 kV ESF buses via the cross-tie to the other reactor unit. The two ESF 4.16 kV and two non-safety 6.9 kV station buses energise the two reactor coolant pumps (RCPs) from each of the SATs (4x RCP's in total, one on each 6.9 kV bus) which are linked to the 345 kV switchyard [12]. The other two non-safety 6.9 kV and the two non-safety 4.16 kV buses (see Figure 3-3), which are energised by the two Unit auxiliary transformers (UATs) 241-1 and 241-2 from the main generator and SATs which have Fast Bus transfer protection schemes. Each generator UAT has a Star- Star winding configuration.

There are two relays to detect low voltage (LV) on the 4.16 kV buses [22]. Each of the relays detects the phase to phase voltage i.e. on phases 'A' to 'B' (V_{ab}) and on phases 'B' to 'C' (V_{bc}) respectively. This is a "two-out-of-two" logic philosophy, which requires both relays to operate in order for the offsite source to be switched to the onsite power [22].

There are also two relays to detect low voltage on the 6.9 kV buses [22]. These relays also detect phase to phase voltage on phases 'A' to 'B' and phases 'B' to 'C'. The difference with these relays is that only one relay is required on two of the four buses, to sense the low voltage, in order for a generator trip signal to be initiated. This is a "one-out-of-two" logic philosophy. When an under-voltage condition is sensed on either of the buses that are supplied by the SAT or UAT, the protection will automatically chop over to the energised transformer [22].

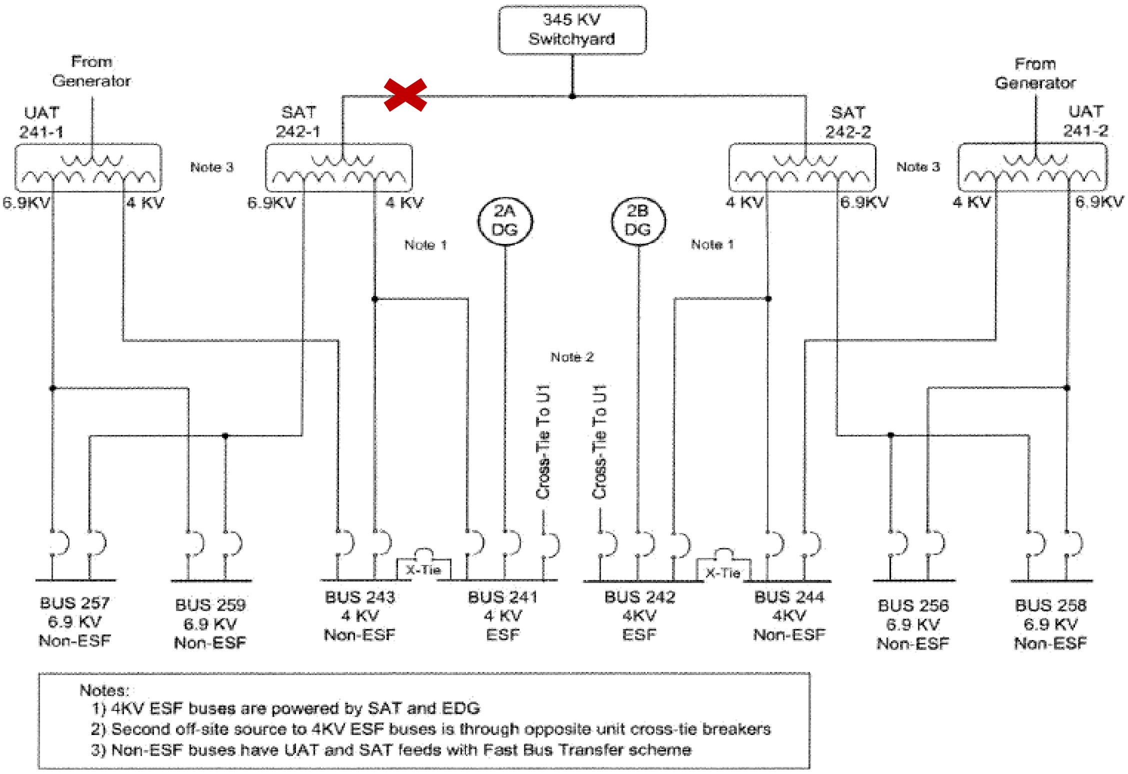


Figure 3-3 Byron NPP Unit 2 cross tie to Unit 1 [21]

- ***EVENT DETAILS***

On the 30th January 2012 at 10:01, in the 345 kV switchyard at BNPS, an Ohio Brass inverted porcelain insulator failed and the conductor fell to the ground, which was an *"open phase non-faulted condition on phase 'C'"* [22] (see Figure 3-4), which occurred on non-safety-related (NSR) equipment.

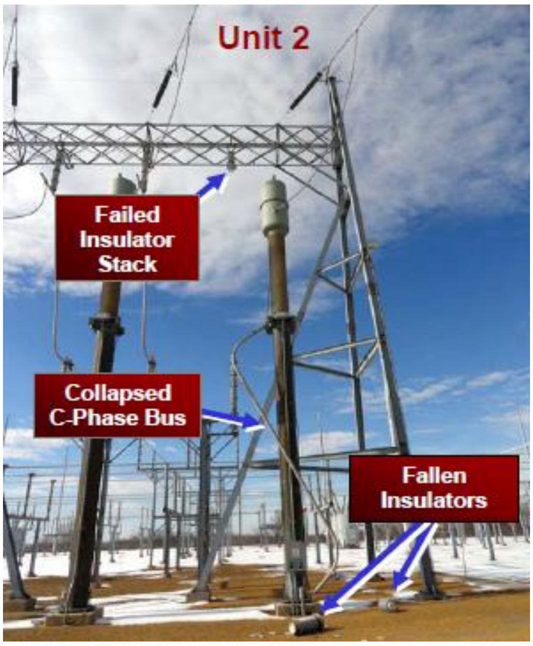


Figure 3-4 OPC phase 'C' at Byron station Unit 2 [11]

At the time of the event, the unit 2 reactor was operating at 100 % power output. The reactor scrammed on reactor coolant pump (RCP) bus under-voltage protection [12]. This occurred when two RCPs 'B' and 'C' out of the four RCPs tripped and sent a reactor trip signal, due to an under-voltage state on the 6.9 kV buses [4]. The under-voltage was due to a broken 345 kV insulator on the 'C' phase that supplies SAT 242-1 and 242-2 of Unit 2. This was a mechanical failure and caused an OPC due to the unbalanced voltage on phase 'C'. The mechanical failure took place between the insulator support A-frame structure and the isolator on bus 13 (see Figure 3-5). The broken off phase 'C' connection was still electrically connected to the transformer, while the loose conductor ends were facing the busbar (BB) fell to the ground [4].

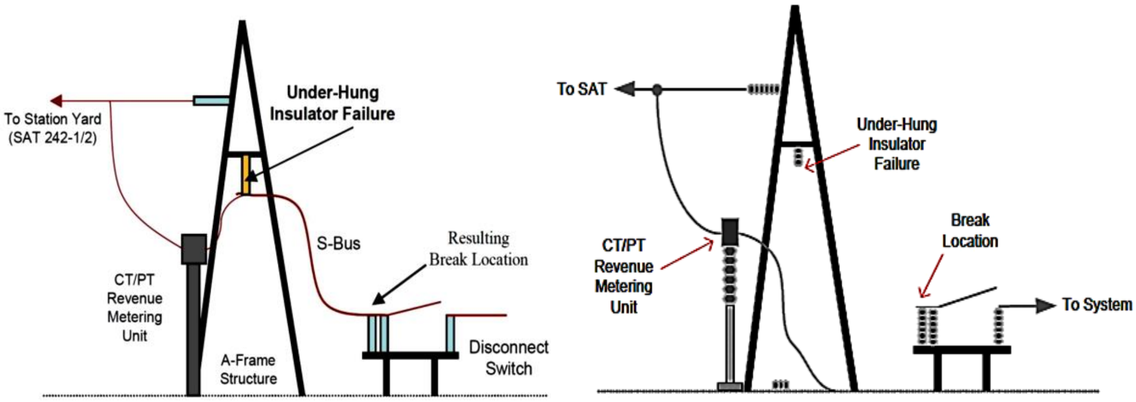


Figure 3-5 Before/After failure at Byron station Unit 2 [11]

The 4.16 kV under-voltage protection on the ESF buses did not automatically chop over to the EDGs. This occurred as the 4.16 kV ESF bus under-voltage "two-out-of-two" logic for the protection was not satisfied [22]. This protection looks at voltage on phases 'A' and 'B' (V_{ab} and V_{bc}) only and both had normal voltages due to the phase angles. The current in phase 'C' was approximately 60A, which was not sufficient for the SAT's overcurrent or differential protection relays to operate [11].

The 6.9 kV NSR buses 258 and 259, which energise the RCPs picked up the under-voltage condition and sent out a trip signal to the reactor, as per design [22]. The 2A motor driven Auxiliary Feedwater (AF) pump and the 2B diesel driven AF pump automatically started. Then the main generator tripped on reverse power 30 seconds after the initial scram [12]. The 4.16 kV ESF buses had an unbalanced voltage condition, but it remained energised. All the circuit breakers tripped to the UAT and to the switchyard. All the busses (6.9 kV Bus 256, Bus 257, NSR 4.16 kV Bus 243 and Bus 244) that were fed by the UAT were transferred to the SAT which was in a degraded state [23]. The current flow increased on the SAT's phases 'A' and 'B' and hence all four of the RCPs tripped on phase 'A' overcurrent. As well as all the loads which were fed by the SAT 242-1 and 242-2 tripped, these loads include the 2A Service water (SX) pump, 2B Centrifugal charging (CV) pump and the 2A Component Cooling water (CC) pump. Due to low suction pressure, the 2B CC pump received a signal to automatically start and it also tripped on phase 'A' overcurrent protection.

After the reactor tripped, at 10:18 a Notice of Unusual Event (NOUE) emergency was declared by the licensee. The nuclear plant was shut down safely [8] as the operators manually tripped the breakers to the offsite power supply from the unit buses.

The control room operators noticed the unbalanced voltage and responded appropriately to the automatic reactor trip, with the correct emergency response procedures. They opened the breakers of the SAT to the ESF 4.16 kV buses. This isolated all the connected loads and the EDG's started up automatically. They performed a natural-circulation to cool down the unit, as there were no operational RCPs available [4].

There was a design vulnerability on the ESF buses i.e. bus 241 and bus 242, which were not originally designed to operate automatically to isolate for the loss of a single phase i.e. phase 'A' or 'C' [23]. Hence, the open phase 'C' didn't generate an automatic under-voltage protection signal for the safety-related (SR) 4.16 kV ESF buses. All the equipment energised from these buses were inoperable and unavailable, until the manual intervention to separate the buses from the degraded offsite supply. The decay heat produced by the reactor was removed by operating the 2B diesel driven AF pump and the Steam Generator (S/G) Power Operated Relief Valves (PORVs). The primary system cooled down via natural circulation and the next day the reactor entered the Cold Shutdown mode.

After the reactor tripped, steam containing low levels of tritium (a radioactive hydrogen isotope) was released from the turbines to assist in cooling the reactor [24]. The US NRC spokeswoman, Viktoria Mitlying told ABC7 news that "They're normal releases that we allow and this is an abnormal release, but it's still far below any limits that we have. There is no threat to the public." [24]

Operators reported seeing smoke from the SAT of Unit 2. After further investigation, it was concluded that the smoke was due to the sudden inrush current from the OPC of phase 'C', which heated up the SAT windings [23]. The 2B main FW pump was damaged, due to the AC lube oil pump trip [12]. If this OPC had continued for a longer duration, then the RCP seals would have been damaged, due to the loss of cooling water for the seals. The OPC caused by an insulator failure in the switchyard exposed vulnerability in the plant's protection scheme.

The loss of one phase between the onsite power source and the switchyard resulted in the inability of the safety features of the onsite and offsite power system [2]. The OPC caused a loss of normal offsite supply and a reactor trip [22].

- ***CAUSE OF OPC***

The Open phase condition occurred due to an Ohio Brass inverted porcelain 345 kV insulator which failed. It failed in an insulator stack on the A-frame structure, which provided vertical support to the 'C' phase conductor of Unit 2 345 kV/6.9 kV SAT 242 (see Figure 3-6). The insulator failed as there was *"service propagation of a large manufacturing material defect that covered 40 % of the fracture cross-section"* [22]. The fracture was due to "*poorly vitrified porcelain*", which had a porosity with a high density and micro-cracks were formed which caused the internal mechanical failure (see Figure 3-7). The poor quality of the porcelain and age were the main reasons for failure.

The design vulnerability was exposed in the protection scheme. There was not adequate detection for a single open phase. This vulnerability in the protection delayed the isolation of the affected section.

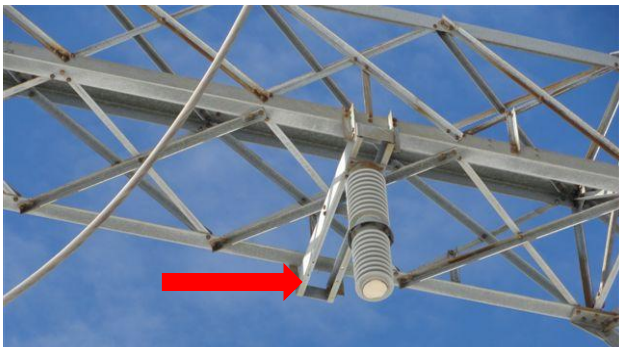


Figure 3-6 Byron Station OPC on SAT 242 failed insulator [12]

Figure 3-7 Byron Unit 2 failed insulator 40 % poor quality porcelain [25]

Another similar event took place at Byron NPP unit 1. Table 3-2 shows a summary of the event and Table 3-3 shows the cause of the OPC event. The full case study can be found in Appendix A2-1 BYRON UNIT 1, ILLINOIS, USA, 28 FEB 2012.

Table 3-2 Byron Unit 1 OPC event summary

When OPC occurred	Date discovered	Where OPC occurred	Discovered by	Reactor type
28/02/2012	28/02/2012	Mechanical failure of a 345 kV under-hung porcelain insulator on 'A' phase of A-Frame structure	Main Control Room Operations crew	Westinghouse-Pressurised Water Reactor (PWR) -2 Units

Table 3-3 Byron Unit 1 OPC event at a glance

Cause of the OPC	Root cause	Contributing cause
Failed inverted Ohio Brass 345 kV insulator on HV side of station auxiliary transformer	Material defect due to poor quality porcelain	-Design Vulnerability in Protection scheme

3.3.2 CONDUCTORS

BEAVER VALLEY UNIT 1, USA, 27 NOV 2007

- ***STATION LAYOUT***

The Beaver Valley Power Station (BVPS) has two 4-loop Pressurised Water Reactor (PWR) units. The NPP is situated near Pittsburgh in Western Pennsylvania in the United States of America (USA). Unit 1 and Unit 2 have an output of 911 MW and 868 MW respectively [26].

Pennsylvania Power Company (65 %) and Ohio Edison (35 %) share the ownership of Unit 1 which was commissioned in 1976. FirstEnergy Nuclear Operating Company (FENOC) operates the plant. Unit 2 which was commissioned in 1987 is owned by Ohio Edison (41.9 %), Toledo Edison (24.5 %), Cleveland Electric Illuminating (19.9 %) and Pennsylvania Power (13.7 %) [26].

Unit 1 has four “train” buses at 4.16 kV each. Buses ‘A’ and ‘D’ each has its own System Station Service Transformer (SSST) which is connected to the 138 kV switchyard via separate offsite feeders. These are normally unloaded during power operation (see Figure 3-8). Buses ‘B’ and ‘C’ are energised from the main generator via the two Unit Station Service Transformers (USSTs), which are trains ‘C’ and ‘D’, respectively.

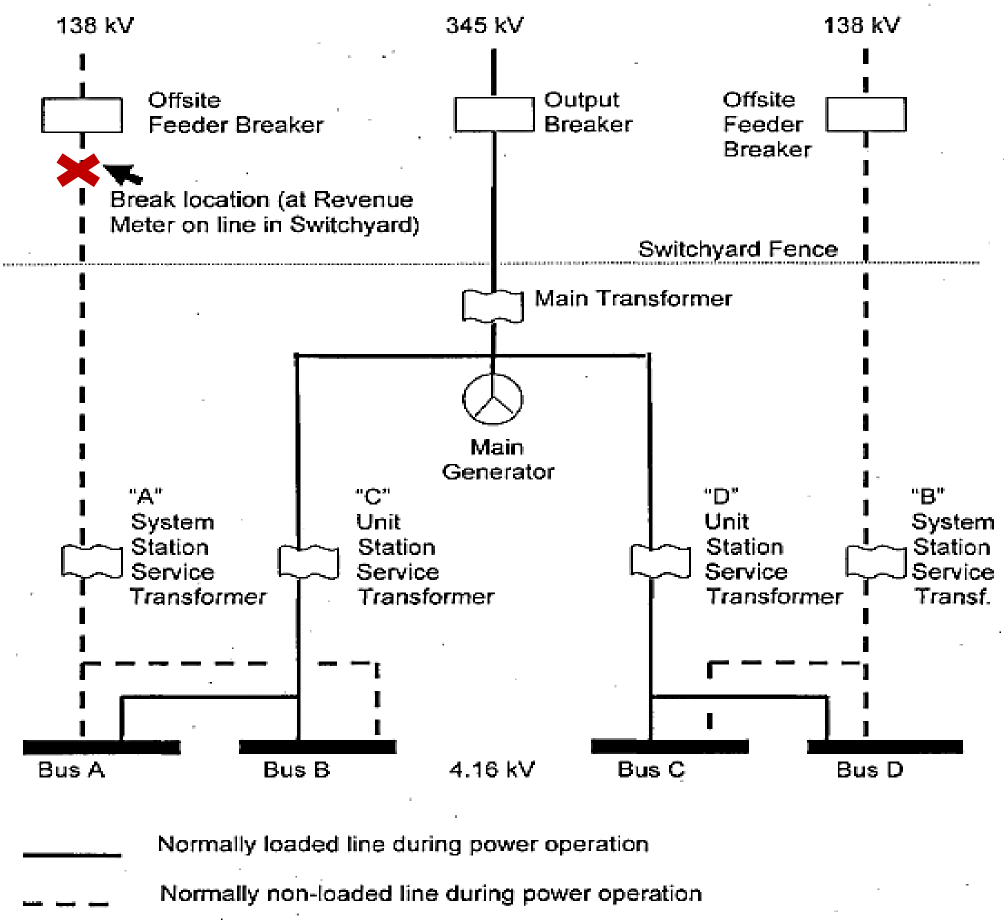


Figure 3-8 Beaver Valley Unit 1 NPP electrical diagram [27]

- ***EVENT DETAILS***

Based on the LER 2007-002-00 ML080280592 [27]; the BVPS-1 was operating at 100 % power output at the time of the event. On the 27th November 2007, a FENCO site construction supervisor at BVPS1 went for a non-routine switchyard walk-down, to investigate the reason for the differences in the line voltages. The phase 'A' 138 kV power line conductor was found broken in the switchyard. The conductor broke between the offsite feeder breaker which was on the switchyard side of the metering current transformer/voltage transformer (CTVT) and the onsite 'A' train SSST (see Figure 3-8). During normal operation, there is no load on this 138 kV line, as the station busbars are energised from the unit generator.

The licensee declared the 'A' train offsite power circuit inoperable at 09:55 on the same day. The 138 kV line was repaired and the 'A' train offsite power circuit was declared operable at 12:53 on the 28th November 2007. After further investigation, it was discovered that the 'A' phase 138 kV conductor break occurred on the 1st November 2007 already, based on the loss of current in the open phase from the computer-based information of the offsite and onsite currents. At BVPS-1 there were no alarms in the control room triggered to indicate that the OPC existed [27].

The BVPS-1 TS 3.8.1 Limiting Condition of Operation (LCO) *"requires that there are **two** qualified offsite circuits between the offsite Transmission network and the onsite Class 1E AC Electrical Power Distribution System should be operable"* [27]. BVPS-1 entered the LCO when one of the two offsite circuits was declared inoperable.

On the 14th November 2007, the offsite power surveillance was done; as minor voltage differences were picked up between the three phases of the 'A' train SSST. The SSST Load Tap Changer was placed on manual in order to return the voltages to limits within the specification.

The stations' Technical Specification Surveillance Requirement (TSSR) 3.8.1.1 is performed every 7 days and states: *"Verify correct breaker alignment and indicated power availability for each required offsite circuit".* The surveillance procedure 1OST-36.7 was "successfully" performed six times from when the OPC occurred to when it was discovered, i.e. on the 2nd, 7th, 8th, 14th (twice) and on the 21st November 2007, without discovering the 138 kV 'A' phase open circuit. The breaker alignments and phase to phase voltages on the secondary side of the SSST are checked during the surveillance. The secondary phase to phase voltages measured were acceptable, as the induced voltages from the 'B' and 'C' phases on the transformer regenerated the lost phase 'A' voltage on the primary side. The transformer was under no-load conditions at the time of the event. The lost phase voltage of the 'A' train caused the SSST to be inoperable as well as the connected offsite safety circuit [27]. As one circuit was declared inoperable, required Action A.3 was to be enforced, where the circuit should be restored within 72 hours. The OPC occurred on the 01st November 2007 (27 days before it was picked up) and went undetected for longer than the allowed 72 hours. The 10 CFR 50.73(a)(2)(i)(B) was then applicable [28]. There was no open phase current instrumentation in the Beaver NPP control room. Therefore, the surveillance procedures were not capable of detecting the Open phase condition.

- ***CAUSE OF OPC***

The Open phase condition occurred due to a conductor which broke at the power cable terminal connection on the ‘A’ phase, between the offsite feeder at the CTVT and the onsite ‘A’ train 4.16 kV/138 kV SSST. The cable did not provide the *“full design cable holding capability”*. The conductor broke due to an “*improper manufacturer's brazing process*” [27].

The OPC was not detected earlier because the BVPS-1 TSSR was not adequate to detect the OPC. Site staff did not have sufficient knowledge regarding the OPC and therefore they did not recognise that it was an OPC, as the other two phases on the secondary side of the SSST was able to regenerate the lost phase ‘A’ voltage.

Another similar event took place at Bruce NPP unit 1. Table 3-4 shows a summary of the event and Table 3-5 shows the cause of the OPC event. The full case study can be found in Appendix A2-2 BRUCE A UNIT 1, CANADA, 22 DEC 2012.

Table 3-4 Bruce Unit 1 OPC event summary

When OPC occurred	Date discovered	Where OPC occurred	Discovered by	Reactor type
22/12/2012	22/12/2012	230 kV conductor on one phase broke off in switchyard on System Service transformer 1	Operators	CANDU-Pressurised Heavy Water Reactor (PHWR)

Table 3-5 Bruce Unit 1 OPC event at a glance

Cause of the OPC	Root cause	Contributing cause
Loose 230 kV conductor on transformer HV side	Incorrect application of jumper connector plate	- Strong winds - Design Vulnerability in Protection scheme

3.4 FAULTY EQUIPMENT

3.4.1 ISOLATORS

JAMES FITZPATRICK & NINE MILE POINT UNIT 1, USA, 19 DEC 2005

- ***STATION LAYOUT***

The James A. Fitzpatrick (JAF) NPP is located in Scriba in New York, on the shore of Lake Ontario. Based on the LER-05-006, the JAF switchyard at 115 kV is energised by two separate TX lines, which are two independent, redundant sources of 115 kV offsite power sources [29]. Fitzpatrick line numbered 3 (Line #3) is called Lighthouse Hill. This TX line, 115 kV Fitzpatrick - Lighthouse Hill No3, connects the South 115 kV yard to the Lighthouse Hill substation. Fitzpatrick line numbered 4 (Line #4) is called Nine Mile. This second TX line, 115 kV Fitzpatrick - Nine Mile No4 connects the North 115 kV bus to the Nine Mile Point Nuclear Station Unit 1 (NMP1).

There are two Reserve Station Service Transformers (RSSTs) T2 and T3, which are energised by the 115 kV TX lines, via a closed busbar isolator. The 115 kV TX system is designed in such a way that either TX line can supply both RSSTs that energise the safeguards buses. In normal operation, all the plant loads are supplied by the SSST T4 and the reserve transformers T2 and T3 are unloaded. The breakers to the reserve transformers T2 and T3 are closed from the 115 kV side, but the breakers on the 4.16 kV are opened [29].

Voltmeters in the control room of the JAF NPP are used to monitor the voltage on both of the TX lines. There is no instrumentation to indicate phase current in the control room. There is under-voltage protection present, which would signal an indication if there were an under-voltage condition due to a fault on either of the lines. If a fault occurred on either line, the other line would not be affected and the equipment will remain stable [29].

- ***EVENT DETAILS***

On the 19th December 2005 at 15:09, while JAF NPP was operating at 100 % power output, the control room at NMP-1 was alerted by the National Grid (NG), that a Traveling Operator found the 115 kV line current readings on the Line #4 were abnormal, which could possibly be due to an OPC. The current readings were 0, 50 and 50 amps, on the ‘A’, ‘B’ and ‘C’ phases respectively. The NMP NPP then contacted the JAF control room and they initiated an investigation. The investigation in the JAF switchyard discovered that there was a Penn Union busbar isolator failure on phase ‘A’ of Line #4 offsite supply [30]. In order for the repairs to take place, that line was declared inoperable and repairs were completed and the line was returned to service the next day. After an investigation, i.e. engineering evaluation, it was discovered that the failure existed from the 29th November 2005 and was only discovered on the 19th December 2005 [28]. This offsite source was out of service (OOS) for 21 days which exceeded the Allowed Out of service Time (AOT). The failure remained undetected for this duration, as there were no alarms in the control rooms to indicate the existence of the OPC. This was the case at the Nine Mile Point Unit 1, James A. Fitzpatrick NPP and at the National Grid.

The following TS were exceeded at NMP-1 [30]:

- TS 3.6.3.b - duration allowed for Emergency Power Sources to be OOS for the inoperability of an offsite line. The Line #4 was inoperable for 21 days (29 Nov - 19 Dec) but the allowed OOS duration is 7 days.
- TS 3.6.3.c - duration allowed for EDG 102 and EDG 103 to be OOS were exceeded. Both the EDGs were inoperable as it was out for planned maintenance. The EDG 102 was inoperable for 4 days (29 Nov - 3 Dec 04:06) and EDG 103 was out from 12 December 16:12 till 17:18 the next day (for 25 hours and 6 minutes), but the allowed OOS duration is 24 hours.

On the 20th December 2005 at 15:12 Line #4 was restored. The Conditional Core Damage Probability (CCDP) was calculated to be 8.7 $X10^{-8}$ for the unavailability of Line #4 [30]. This CCDP is an indication of the likelihood that an accident could occur to damage the reactor core and the nuclear fuel [31].

- ***CAUSE OF OPC***

The Open phase condition occurred due to a Penn Union busbar isolator broke off on the 115 kV Fitzpatrick - Nine Mile No4 TX line at JAF NPP. The isolator failed due to “mechanical overload”. It is speculated that there was mishandling of the isolator connections during the previous maintenance, which increased the stress on the isolator parts. The maintenance procedures, MP-071.61 did not provide sufficient details on how to handle and properly disconnect the components. Adverse weather conditions i.e. wind, cycling temperatures, ice loading also added to the stress on the connections [29].

The Open phase condition was not detected earlier, as the existing current loading indications installed for both offsite supplies at NMP1, did not indicate the OPC. This was due to the abnormal operating value falling in an “uncalibrated and unmarked area of the meter” [30]. The alarms and indications on the Ring bus protection at JAF and NMP1, to notify the control operators of the abnormal situation, were not adequate. There was a design deficiency in the protection, as the protection was not designed to “see” nor operate for an OPC. The surveillance test (ST) 9W - “Electrical Line-up and Power Verification” procedures were inadequate at JAF, as it requires the busbar voltages to be monitored every 7 days, but the current readings of all three phases were not included to be checked.

3.5 SWITCHING OR MAINTENANCE

3.5.1 LOOSE CONNECTIONS

FORSMARK UNIT 3, SWEDEN, 30 MAY 2013

- ***STATION LAYOUT***

Forsmark Nuclear Power Plant (FNPP) is situated in Forsmark, Sweden on the East coast. The NPP is approximately 4 km North of Östhammar Municipality in Uppsala County [32]. The NPP was built and is operated by Forsmark's Kraftgrupp Aktiebolag (FKA). The license holder is FKA and the NPP has 3 units each being the Boiling Water Reactor (BWR) manufactured by Westinghouse Electric (previously ASEA-ATOM). Each unit's power generation is 984 MW, 996 MW and 1170 MW respectively [32]. All three units are generation III Advanced BWRs.

FNPP has three independent 400 kV lines connecting it to the NG and two 70 kV lines connecting it to the Regional grid [32]. The Forsmark Unit No1 and No2 are light water reactors, type BWR69 and use the same switchyard for two 400 kV lines. Forsmark Unit No3, which is a newer light water reactor, type BWR75 has a separate 400 kV switchyard. All reactor units share the same 70 kV switchyard. There are two offsite supplies that feed Unit 3 and it has four dedicated individual EDG's. There are four trains in each of the three units (see Figure 3-9). This is to adhere to the single failure criterion.

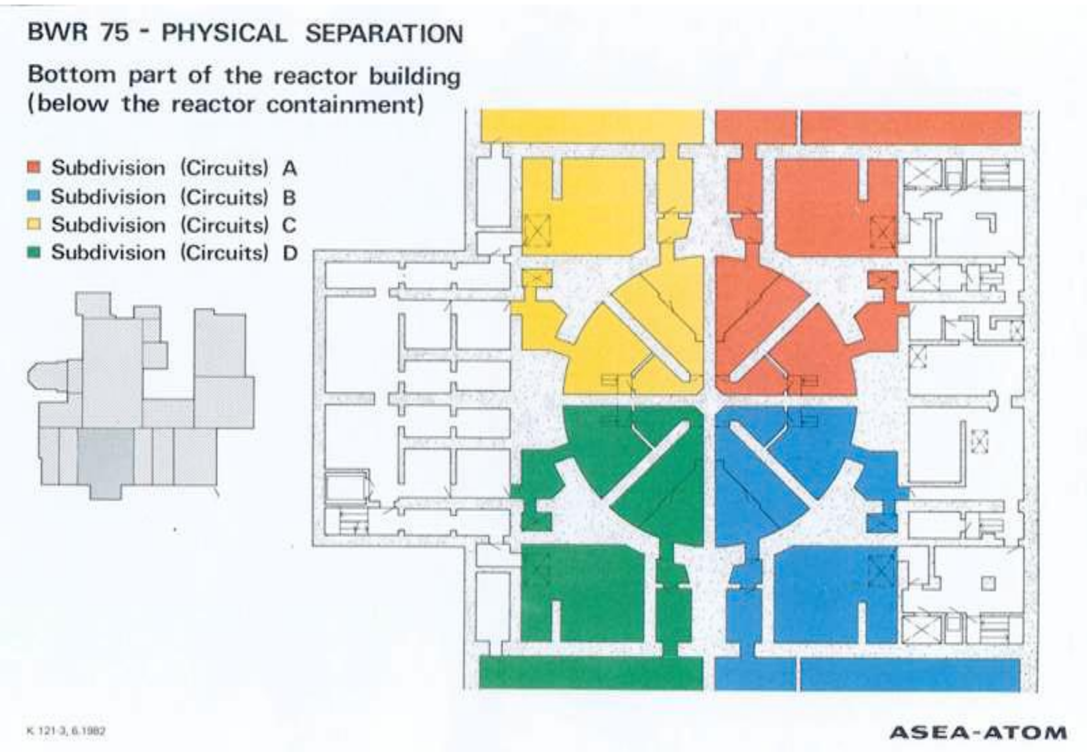


Figure 3-9 Four Train layout for Forsmark Unit 3 NPP [32]

- ***EVENT DETAILS***

On the 30th May 2013, there was a refurbishment/refuelling outage and planned maintenance on Forsmark Unit 3. During this outage, the 70 kV grid supply was switched out, in order for them to connect Unit 3 to the new 70 kV switchyard [33]. And one of the two 400 kV offsite supply lines had its breaker open due to the maintenance. A "mistake" caused by human error, resulted in a single OPC [15]. The human error occurred while protection staff was testing the relays on the main generator, using a new method of testing. A trip signal was sent incorrectly to the closed 400 kV breaker of the offsite supply line that was in service at the time. The signal that initiated the trip was generated from the negative sequence relay testing [33]. A double Open phase resulted, as only two of the three phases of the 400 kV circuit breaker poles opened [15]. The safety and non-safety related (NSR) equipment overheated and tripped. On the safety buses, the existing under-voltage relays, which measure positive sequence, did not pick up the OPC. The voltages were induced in the other phases and the relay's trip set point was lower than the induced voltage (due to low loading), hence it did not trigger [15]. The standby AC power did not initiate, due to the undetected loss of voltage [2]. Train 'A' and Train 'B', as well as standby AC powered Train 'C' and Train 'D', were available for operation due to the double OPC.

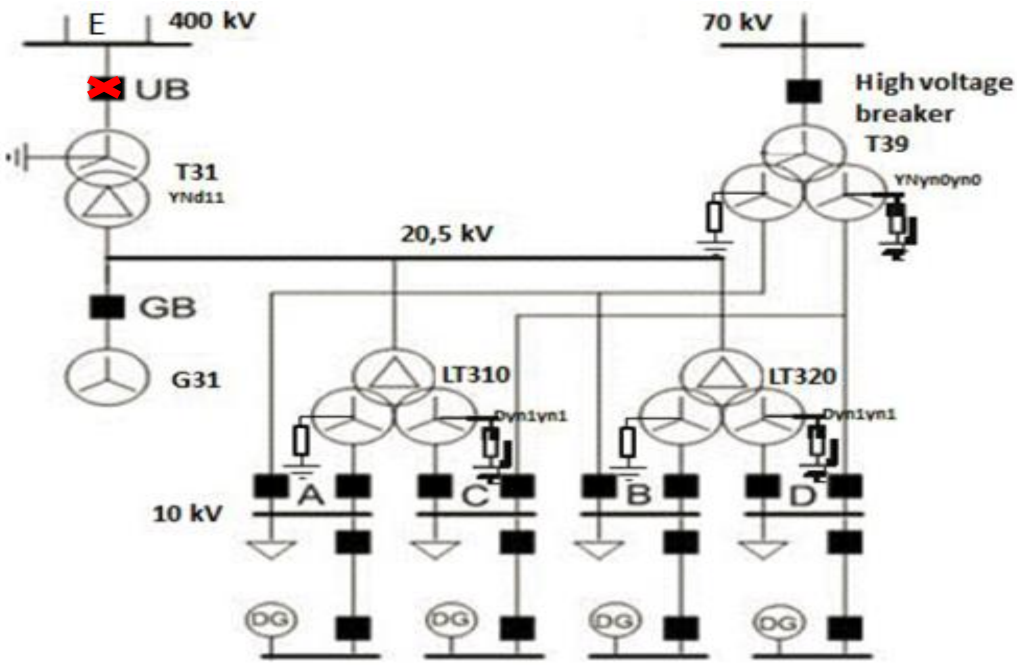
There was a voltage unbalance and this caused the connected loads, which had unbalance protection relays, to trip. Hence, the important-to-safety residual heat removal (RHR) of the fuel pools and cooling system for the standby AC power tripped [2]. The under-voltage protection was set to operate at 65 % symmetrical components value and positive sequence filtering was available. The phase to phase output of the under-voltage protection is a mean value; hence the EDG did not start automatically as the voltage was not below the settings pick up value of 65 % [33].

Operators had to manually intervene by starting the EDG's; they initiated the standby AC power and opened the circuit breakers. The manual action of the operators also restored the cooling to the spent fuel pool. They also had to manually reset all the imbalance relays, as the safety loads were supplied from the standby AC power supply [2]. After further investigation, it was found that there was a loose cable in the circuit of the 400 kV breaker. This caused the double OPC. Equipment, such as the non-safety motors were damaged during the double OPC [2]. Table 3-6 shows the status of the plant before the OPC:

Table 3-6 Forsmark status of plant before the OPC

Plant	Status	Reason
70 kV grid	Off line	New 70 kV switchyard to be connected
400 kV Bus 'D'	Off line	Work was on-going
Train 'A' and 'B'	On standby	Available for operation
Train 'C' and 'D'	Off line	Maintenance was on-going
EDG on Train 'C' & 'D'	On standby	Available for operation
Generator	Off line	Protection tests on excitation system

On the day at 10 o'clock in the morning, the indication for the 400 kV breakers on Bus 'E' for the Unit breaker (UB) on the main transformer (MT) T31 indicated that it was in transit, i.e. in an intermediate position [33]. This was due to one of the three phases still being in the closed position. This main transformer has a Star-Delta (YNd11) winding configuration. The inadvertent trip caused phase discrepancy protection to operate and to trip the plant that had this protection installed. The decay heat removal, which is important-to-safety equipment, also tripped. The heat removal was offline for 17 minutes and consequently the fuel pool temperature increased by 0.7^{o}C [2] . The supply to the 400 kV Bus 'E' was restored 44 minutes after the initial trip. The buses did not have the phase discrepancy protection installed. This caused the 400 kV grid and the system that is supplied by the diesel generators i.e. 10 kV Bus 'A', 'B', 'C' and 'D' not to disconnect (see Figure 3-10). It was also found that the under-voltage protection installed did not operate for the OPC, on the NSR busbar and the safety busbar (supplied by the diesel generators) [33]. The maintenance procedure was not updated to reflect that the protection testing was revised from a one phase model to a three-phase model.



Legend
UB = Unit Breaker or Grid breaker
GB = Generator Breaker
T31 = Generator Step-up Transformer or Main Transformer
T39 = Startup Transformer or Station Transformer
LT = Unit Auxiliary Transformers
G31 = Main Generator

Figure 3-10 Single line diagram of Forsmark Unit 3 NPP [33]

- ***CAUSE OF OPC***

The Double OPC occurred due to an erroneous trip signal that was sent to the 400 kV circuit breaker during testing of the generator protection. The incorrect signal was sent due to human error and only two of the three phases of the 400 kV unit circuit breaker opened, it occurred due to a loose cable connection in the tripping circuit of the 400 kV breaker. There was a loose cable in the circuit because it was not terminated correctly nor checked during the maintenance. Due to oversight it was not picked up and the maintenance report was not updated to reflect the change in the protection testing method from using a one-phase model to a three-phase model.

Another similar event took place at Vandellos NPP unit 2. Table 3-7 shows a summary of the event and Table 3-8 shows the cause of the OPC event. The full case study can be found in Appendix A2-3 VANDELLOS UNIT 2, SPAIN, 9 AUG 2006.

Table 3-7 Vandellòs Unit 2 OPC event summary

When OPC occurred	Date discovered	Where OPC occurred	Discovered by	Reactor type
09/09/2006	09/09/2006	400 kV cable on 'R' phase broke off in switchyard	Operators	Westinghouse-Pressurised Water Reactor (PWR) -1 Unit

Table 3-8 Vandellòs Unit 2 OPC event at a glance

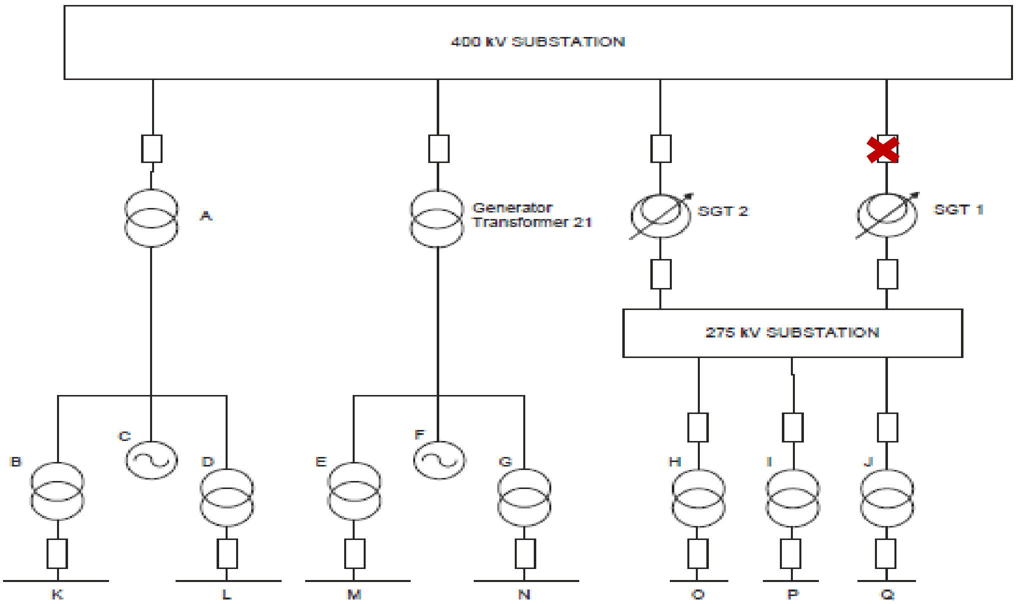
Cause of the OPC	Root cause	Contributing cause
Loose 400 kV cable on transformer HV side to support insulator	Insulator rotating annular contact burned off	- Design Vulnerability in Protection scheme

3.5.2 BREAKERS

DUNGENESS B UNIT 22, UK, 14 MAY 2007

- ***STATION LAYOUT***

Dungeness B NPP (DNPP B) is situated in Kent in South East England coast on the Shingle bank, United Kingdom. This plant has two units at 600 MW each, which are Unit 21 and Unit 22. DNPP B is owned and operated by EDF Energy. The reactor type is an Advanced Gas Cooled Reactor (AGC). Each unit has its own 400 kV/3.3 kV Generator Transformer which is Star-Delta winding, and there are two Super grid Autotransformers 400 kV/275 kV, SGT1 and SGT2. There are three 275 kV/11 kV Station transformers, i.e. 21, 21A and 23 which is Star-Delta winding, which supply the 11 kV system from the 275 kV switchyard. The two unit transformers 3.3 kV/11 kV for each reactor unit, which is Star-Delta connected and the Star windings are interconnected with each other. The NPP equipment on Reactor Unit 21 and Unit 22 are integrated for redundancy (see Figure 3-11). The unit transformers supply the 3.3 kV essential and backup (BU) supply systems. The main generator does have negative phase sequence (NPS) protection installed. The 400 kV network as well as the Bus coupler is owned by the Grid Operator.



A: Generator Transformer 22
B: Unit Transformer 22B
C: Generator 22
D: Unit Transformer 22A
E: Unit Transformer 21B
F: Generator 21
G: Unit Transformer 22
H: Station Transformer 21A
I: Station Transformer 23
J: Station Transformer 21

K: 11 kV Unit Board 22B
L: 11 kV Unit Board 22A
M: 11 kV Unit Board 21B
N: 11 kV Unit Board 21A
O: 11 kV Station Board 22
P: 11 kV Station Board 23
Q: 11 kV Station Board 21
SGT1: Super grid autotransformer
SGT2: Super grid autotransformer

Figure 3-11 Single line diagram of Dungeness Unit 21 & Unit 22 [2]

- ***EVENT DETAILS***

On the 14th May 2007, the Super Grid Autotransformer 1 (SGT1) and station transformer 21A which normally supplies the 275 kV switchyard was switched OOS. At the time, Unit 22 was operating at 490 MW power output and Unit 21 was on outage. SGT2 was supplying the operating station transformers 21 and 23. During the following three days various motors experienced voltage faults and trips that seemed to be random and unrelated [2] all the following equipment tripped on thermal overload:

- Chiller 21A
- Cooling water pump 21
- Cooling water pump 23
- Turbine 21 aux lubricating oil pump
- Active supply areas and extract fans

Operators investigated and found small voltage deviations of 1.6 % on the 11 kV station boards, which was accepted as normal and did not indicate any abnormality [2]. Operators found it challenging to diagnose the OPC, as there was still continuity of supply and the available voltage measurements did not detect any faults.

After an investigation by the grid operator, they found that the HV circuit breaker of SGT2 was partially opened. This caused the OPC. The SGT2 was also lightly loaded and regenerated the voltages on the open circuited phase [2]. SGT1 was returned to service and SGT2 was taken out to do repairs on the transformer breaker. The last maintenance carried out on this circuit breaker was on the 23rd April 2007. It was speculated that the defect was present since that time, as it cannot be confirmed if the breaker was operated after the maintenance was carried out [2]. The OPC was not discovered earlier, as both Super Grid Autotransformers SGT1 and SGT2 are run in parallel and they are lightly loaded to 6 % of their nominal rating.

- ***CAUSE OF OPC***

The Open phase condition occurred due to a latent defect that was present in the 400 kV circuit breaker of the Super Grid Autotransformer SGT2. The latent defect was due to the breaker pole not making proper contact. The open circuit in the breaker could be due to a “maintenance induced defect” [2].

Another similar event took place at Dungeness B NPP Unit 22. Table 3-9 shows a summary of the event and Table 3-10 shows the cause of the OPC event. The full case study can be found in Appendix A2-4 DUNGENESS B UNIT 22, UK, 27 APR 2014.

Table 3-9 Dungeness B Unit 22 OPC event summary

When OPC occurred	Date discovered	Where OPC occurred	Discovered by	Reactor type
Unkown	27/04/2014	400 kV Bus coupler breaker pole contact	Main Control Room Operators	Advanced gas cooled reactor (AGR) -2 Units

Table 3-10 Dungeness B Unit 22 OPC event at a glance

Cause of the single OPC	Root cause	Contributing cause
400 kV Breaker pole did not make proper contact on the bus coupler on the transformer HV side	Maintenance induced latent defect	- Design Vulnerability in Protection scheme

Another similar event took place at Balakovo NPP Unit 1 and Unit 3. Table 3-11 shows a summary of the event and Table 3-12 shows the cause of the OPC event. The full case study can be found in Appendix A2-5 BALAKOVO UNITS 1 AND 3, RUSSIA, 25 FEB 1997.

Table 3-11 Balakovo Unit 1 and Unit 3 OPC event summary

When OPC occurred	Date discovered	Where OPC occurred	Discovered by	Reactor type
25/02/1997	25/02/1997	Open circuit in 220 kV breaker in switchyard on HV side of Main transformer 1 (T-1)	Operators	Water water energy reactor (VVER 1000)- 4 Units

Table 3-12 Balakovo Unit 1 and Unit 3 OPC event at a glance

Cause of the single OPC	Root cause	Contributing cause
Open circuit in the 220 kV HV breaker on the 'A' phase of the Main transformer T-1	Moisture ingress caused loss of compressed air pressure	- Design Vulnerability in Protection scheme
Undetected earth fault in phase 'B' current transformer of Unit transformers 3T-1 and 3T-2	Design deficiency of differential bus duct protection of units 2, 3 and 4	- Design Vulnerability in Protection scheme

3.6 TRANSFORMER CONNECTIONS

OCONEE UNIT 1 & 3, US, 7 & 15 DEC 2015

- ***STATION LAYOUT***

The Oconee Nuclear Station (ONS) has Reactor Units 1, 2 and 3, which are PWRs manufactured by Babcock and Wilcox with an output of 846 MW each [34]. This nuclear power plant is situated in Seneca, South Carolina in the United States of America. It is owned by Duke Energy Carolinas and operated by Duke Power. This US NPP is the only one that does not have EDGs on site [35]. In the place of EDGs, it has two hydroelectric emergency power sources, i.e. K1 and K2 (see Figure 3-12.) These hydroelectric units are located at the Keowee Dam [35]. The three reactor units each have their own Main transformer (MT1, MT2 and MT3) and Auxiliary Transformer (UAT1, UAT2 and UAT3). The HV side of MT1 and MT2 is supplied from the 230 kV switchyard. While the HV side of MT3 is supplied from the 525 kV switchyard. There are three startup transformers CT1, CT2 and CT3 that are connected to the 230 kV switchyard.

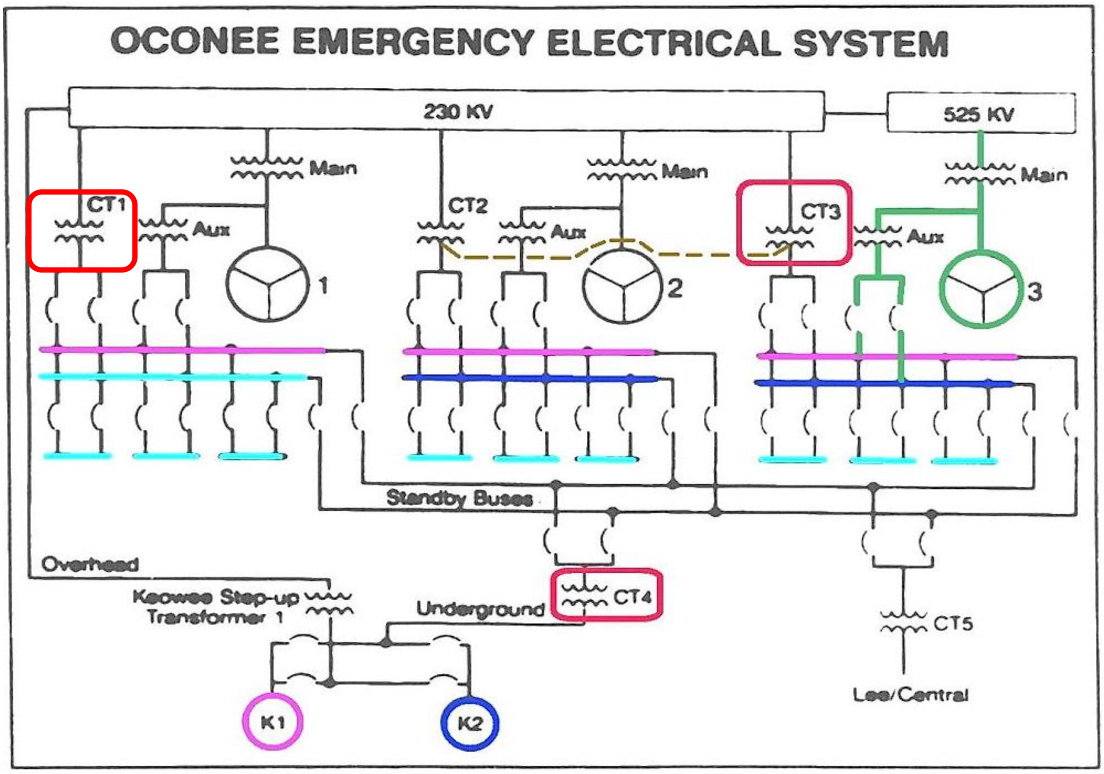


Figure 3-12 Oconee Nuclear Station layout [35]

- ***EVENT DETAILS***

On the 7th December 2015 an auxiliary operator (AO) at ONS was doing his plant observations. On Unit 3 on the 230 kV line in the switchyard, he identified that the conductor to the 230 kV 'Y' phase bushing on the startup transformer CT3 had broken off. He reported his observations to his senior reactor operator (SRO), who was incapable of recognizing the effects on the transformer [36]. The technical engineering support was called in to make an assessment and the unit 3 start-up transformer was declared to be inoperable by the control room supervisor, and the unit entered the TS 3.8.1 Condition A [36]. CT3 was isolated and repairs were carried out, the clamp and conductor were sent to McGuire Nuclear Plant laboratory for examination. Available protection relays that were installed were not able to detect the open phase, especially as the startup transformers were unloaded.

A week later on the 15th December 2015, after carrying out an extent-of-condition review on all the transformer bushing connections, it was discovered that all three 230 kV phases of CT1 also had broken cable strands. Varying number of Aluminium (Al) strands was broken off on each phase (see Table 3-13). The CT1 was isolated for repairs and the following was found:

Table 3-13 Broken Startup Transformer conductor strands

	No. of broken Al strands	Iron centre core
CT1 'X' phase bushing	All 6	Intact
CT1 'Y' phase bushing	5 out of 6	Intact
CT1 'Z' phase bushing	1 out of 6	Intact
230 kV overhead line 'X' phase	2 out of 6	Intact

The damaged power cable phase ends were cut off and reconnected, Unit 1 startup transformer CT1 was returned to service on the 16th December 2015. The NRC was requested by the Licensee of ONS, to do a Special Inspection into the "*circumstances surrounding the power cable failures/degradation on the Units 1 and 3 startup transformers.*" A Special Inspection Team (SIT) was selected and issued an inspection report on their assessment which is documented in ML16057A062.

- ***CAUSE OF OPC***

The Open phase condition occurred due to broken Aluminium strands in the 230 kV power cable on the 'Y' phase bushing of the startup transformer CT3 on the HV side. The Aluminium strands broke off due to "excessive flexing" and fatigue [36].

Another similar event took place at Kalinin NPP unit 1. Table 3-14 shows a summary of the event and Table 3-15 shows the cause of the OPC event. The full case study can be found in Appendix A2-6 KALININ UNIT 1, RUSSIA, 13 MAY 1994.

Table 3-14 Kalinin Unit 1 OPC event summary

When OPC occurred	Date discovered	Where OPC occurred	Discovered by	Reactor type
13/05/1994	13/05/1994	Autotransformer AT1-750 power cable broke off at transformer 750 kV 'B' phase bushing	Operators	Water water energy reactor (VVER 1000)- 4 Units

Table 3-15 Kalinin Unit 1 OPC event at a glance

Cause of the single OPC	Root cause	Contributing cause
750 kV Autotransformer bushing connection at the clamp broke off	Fatigue induced fracture	- Design Vulnerability in Protection scheme

3.7 CORRECTIVE ACTIONS

According to the IAEA safety report, the corrective actions were identified and should be implemented as per site specific requirements. Permanent corrective actions should be based on possible online protection detection schemes, which are focussed on monitoring the Open phase condition. This will be dependent on the simulation evaluation results of the plant specific effects. In the next two subsections, the corrective actions undertaken by James FitzPatrick and Beaver NPP are outlined, the other NPPs implemented similar corrective measures.

3.7.1 JAMES FITZPATRICK

At James A. Fitzpatrick NPP (JAF) based on LER 2005-006-00 ML060610079 [29] and Nine Mile Point Nuclear Station Unit 1 (NMP1) LER 2005-004-00 ML060620519 [30], they took the following corrective actions:

- At NMP1 - Implement an alarm modification on the plant process computer, to indicate low current conditions on the three phases of all offsite supply lines.
- At JAF and NMP1 - The current readings on all offsite supply lines (all 3 phases) will be logged, twice during each shift and it should be included in the Operations Shift Standing Order (OSSO) 05-001.
- At JAF - Visual inspections were done on similar isolators on both offsite 115 kV TX lines.
- At JAF - the “Electrical Line-up and Power Verification” ST-9W will be revised to include the criteria from the OSSO 05-001.
- At JAF - the following tests: ST-9W “Electrical Line-up and Power Verification” and ST-9R “EDG system quick start operability test and offsite circuit verification” would be revised to require the NG to confirm that they are reading the correct current values on the TX 115 kV lines.
- At JAF - the maintenance document MP- 071.61 “115 kV Oil circuit breaker maintenance” will be revised, to reduce the probable increase in stress in the busbar isolators.
- At JAF - Outages were required on the 115 kV bus and transformer, in order to do detailed inspections on the remaining eleven isolators on Line #3 and #4.

3.7.2 BEAVER VALLEY

At BVPS based on the LER 2007-002-00 ML080280592 [27], they took the following corrective actions:

- An Operations Standing Order was put in operation at both Units, where physical site walk downs were required to take place with the surveillance of the power station.
- The Kuhlman Electric Model Revenue Metering CTVT on the ‘A’ phase was removed and a jumper was placed to bypass it.
- Surveillance criteria were evaluated of each piece of equipment and enhancements incorporated to verify the availability of the offsite power source during loaded and unloaded network configurations.
- Revise and update the surveillance procedures.
- Additional enhancements were also evaluated to enable the station to detect and identify an OPC on each 138 kV offsite power line.
- All the Revenue Metering CTVTs at BVPS on Unit 1 and Unit 2 have been removed.

3.8 SUMMARY

Based on the operating experience as detailed in the case studies and listed in Table 3-1, it can be deduced that there have been 10 Open phase condition events prior to the occurrence at Byron NPP in 2012. There was not sufficient prior awareness of this phenomenon, as there was after the Byron event took place. The categorisation of the events into the 4 groups, i.e. Material weakness, Faulty equipment, Switching or maintenance and Transformer connections enables the events to be grouped and the OE can be easily extracted.

Based on the operating experience, both temporary and permanent corrective actions arose. These were required to be put in place at all the affected nuclear plants. Amongst others there is a need for constant walk downs in the TX switchyards; maintenance and operating documentation should be regularly checked and revised; operators in the nuclear plant and transmission substation should be frequently trained to promptly diagnose this condition.

CHAPTER 4 KOEBERG OPC EVENT

4.1 INTRODUCTION

Koeberg Nuclear power station (KNPS) is the only nuclear power plant in South Africa, as well as on the continent of Africa [37]. It supplies 5 % of the base-load power to the national grid [38]. This chapter includes the details of the Open phase event that occurred in the KNPS on the 11th November 2005, which resulted in a Blackout in the Western Cape. This event is categorised as Category B- Faulty equipment: Isolators.

4.2 OPC EVENT

4.2.1 STATION LAYOUT

KNPS is situated on the Atlantic coast in Duynefontein, about 30 km North of Cape Town in South Africa. This NPP is the only base load generation situated in the Western Cape Province. KNPS has two PWR units, which were manufactured in France by Framatome. Each unit has three loops in the primary system [33]. The reactor unit also has two dedicated EDG's and there is an additional diesel generator that can supply either unit. Each generator produces about 970 MW. KNPS is owned and operated by Eskom holdings, which is a state-owned utility. Koeberg was designed to withstand earthquakes and was built on an aseismic raft. The reactor is cooled by pumping the cold Atlantic Ocean water at 80 tons/second in its tertiary loop [37]. There are three 400 kV TX feeders and two 400 kV lines linking Koeberg NPP to Ankerlig OCGT (Open Cycle Gas Turbines) Power station. There is a dedicated 132 kV offsite supply feeder to Koeberg NPP, fed from Acacia Gas turbine power station. Acacia is a Peaking Power Station, with three gas turbine generators which are like the engines of a Boeing aircraft [39] (see the right-hand side of Figure 4-1).

There is one Star-Delta main transformer which is used to step up the voltage from 24 kV to 400 kV as well as one 24 kV/6.6 kV/6.6 kV Star-Star-Star unit transformer for each reactor unit (see Figure 4-1). There are also two 132 kV/6.6 kV Star-Delta Auxiliary and two 400 kV/132 kV Star-Delta coupling transformers per reactor unit.

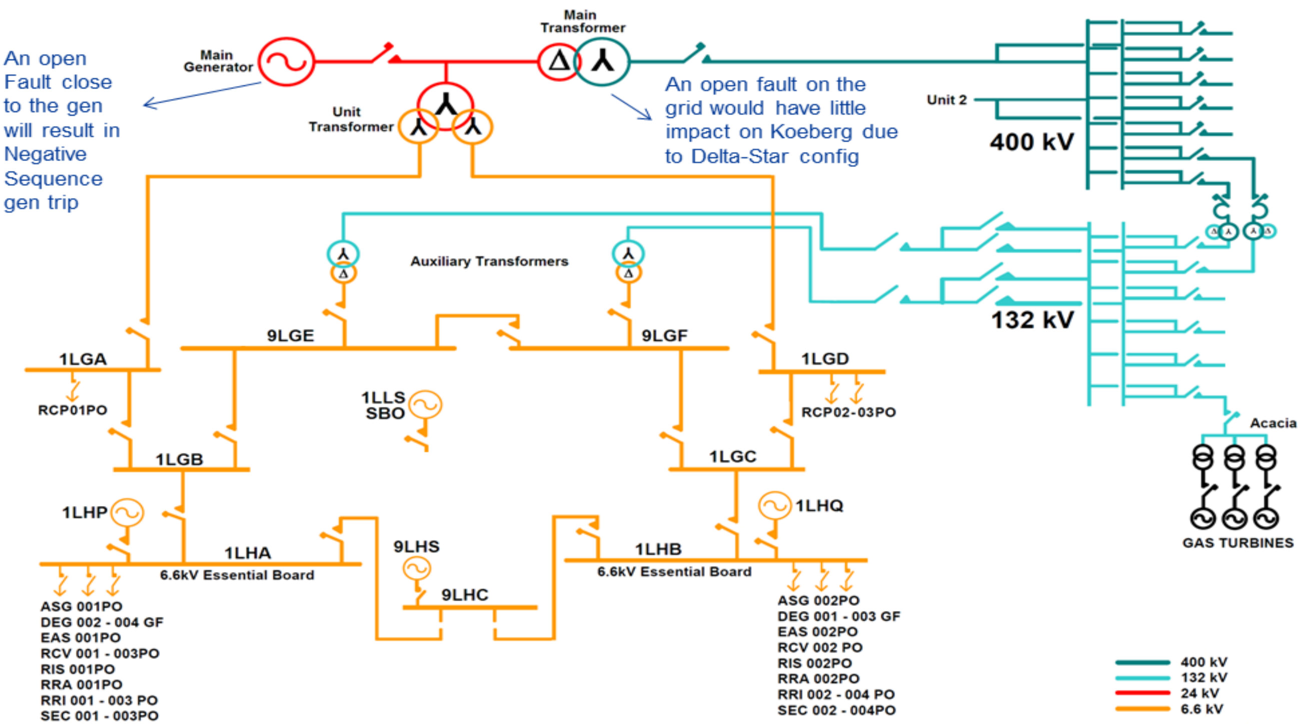


Figure 4-1 Electrical diagram of Koeberg NPP Unit 1 [33]

The double busbar (BB) configuration was implemented in this station on the 400 kV and 132 kV BBs. The 400 kV BB1 and BB2 have two sections each, i.e. section 1A, 1B and section 2A, 2B respectively. The sections are coupled by Bus section (BS) 1 for BB1 and BS2 on BB2. There are two Bus couplers namely 'A' and 'B'. Bus coupler 'A' connects section 1A and 2A and Bus coupler 'B' connects section 1B and 2B, see Figure 4-2 for the station busbar layout. The 400 kV and 132 kV TX busbars are encapsulated in Sulphur hexafluoride (SF_6) gas as indicated in orange in Figure 4-2. The Gas Insulated Switchgear (GIS) uses the gas as an insulation medium. The 400 kV and 132 kV feeders use Air Insulated Switchgear (AIS). This nuclear power station is surrounded by many hectares of nature reserve, which houses several different species of animals and birds.

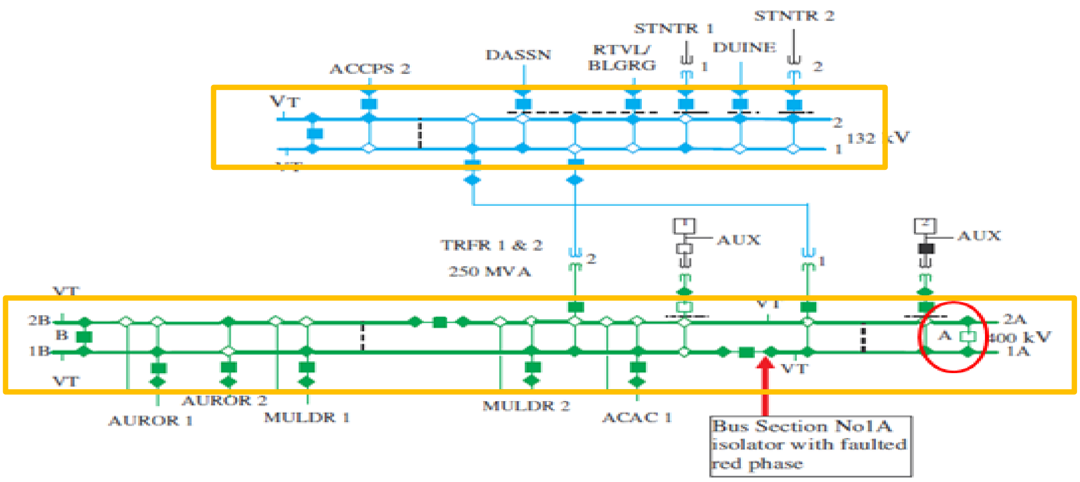


Figure 4-2 Single line diagram of Koeberg TX switchyard in 2005 [40]

4.2.2 EVENT DETAILS

On the 11th November 2005, switching was taking place in the 400 kV GIS switchyard at Koeberg NPP, with the Unit 2 reactor operating at full power output [33]. The switching was to swing the 400 kV feeders and coupling transformer away from busbar 2 and link it to busbar 1, to energise the Koeberg Generator transformer on busbar 2. The switching revealed hidden defects in the plant.

- ***LATENT DEFECT #1***

An open circuit was found on the red phase BS isolator 1A that caused the TX feeders on that section to trip as well as the Koeberg Unit 2 generator. The defect was revealed after the 400 kV Bus coupler 'A' breaker was opened.

At the time of the event, Unit 1 was on outage for refuelling. A total generation of 1326 MW was lost to the Western Cape and resulted in a blackout for minimum of 90 minutes i.e. load-shedding [2]. The 400 kV GIS busbars were normally operated in parallel and the isolator defect was hidden as there were healthy voltages on both sides, which were supplied from Koeberg unit 2, until the busbars were split due to the switching [33].

The GIS isolators are designed to operate from a single drive mechanism. The three isolators are connected to the drive through a coupling shaft to a gear system [41]. The isolator material failed due to deformation that changed the outline of the isolator connection to create the latent defect [33]. This deformation caused the shaft and gear mechanism to be displaced. The gears on the end of the white-to-blue-to-red phase coupling shaft can be seen in Figure 4-3. The red phase shaft was removed, which pulled out of its gear housing. This effectively disconnected the isolator drive from the isolators (see Figure 4-4).

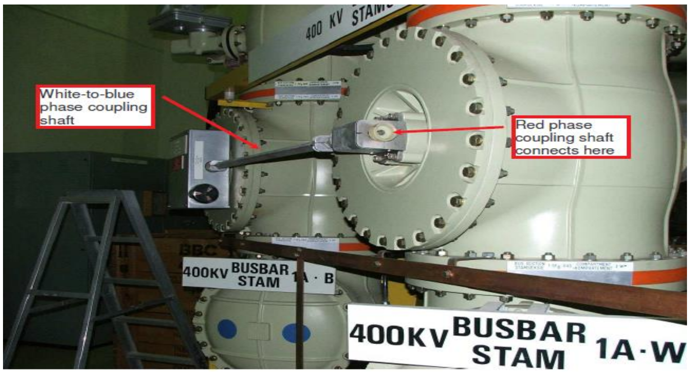


Figure 4-3 KNPS isolator arrangement [41]

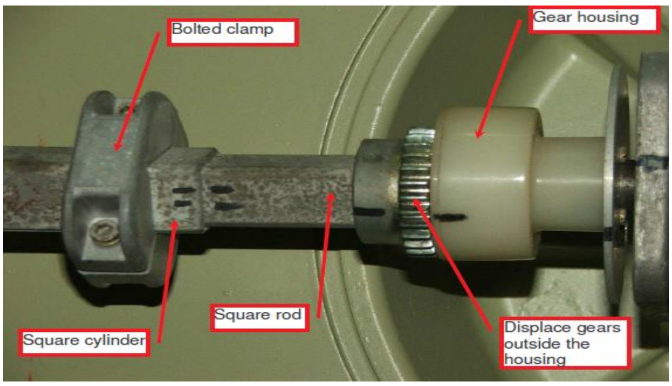


Figure 4-4 KNPS Isolator driving shaft [41]

After investigation it was found that there was a shaft displacement (clean area see Figure 4-5). The open circuit on the SF_6 isolator was not sensed by the protection relays. The procedure states that the isolators must be confirmed to be in the closed state before continuing with switching [2]. During the analysis of the incident, it was concluded that if the operators performed a "risk of trip" assessment the incident could have been averted. In order to pick up these types of defects, the SF_6 isolator circuits need to be manually checked before switching takes place.

Figure 4-5 Red phase bus section 1A isolator displaced shaft [41]

- ***LATENT DEFECT #2***

The Koeberg license conditions states that the KNPS should be able to withstand a 30 % drop in voltage for duration of 2.5s [2]. It was found contrary to the settings implemented. During commissioning a latent defect occurred, where the relay's circuit was incorrectly set to trip for voltage or current dips, where the duration of the loss of supply was not set. The investigation also revealed that the Koeberg Unit 2 did not island from the 400 kV busbar. The direct cause of the unit trip was due to the protection relays for "rapid power loss" not being configured correctly. The unit was unable to island as required due to the commissioning errors. It took Eskom and the municipalities approximately 90 minutes to restore the supply to the customers [42]. The Power station initiated the Koeberg Auto Start (KAS) protection, which was implemented successfully. KAS commences when the 132 kV BB voltage or frequency decreases below a certain value [41].

The unit 2 at Koeberg NPP was returned to service on the 13th November 2005. In Figure 4-6, all the events are displayed in a diagram and Table 4-1 shows the event summary.

Table 4-1 Koeberg Unit 2 11 Nov 2005, OPC event summary

When OPC occurred	Date discovered	Where OPC occurred	Discovered by	Reactor type
11/11/2005	11/11/2005	400 kV Red Phase Bus section 1A isolator had a loose connection	Operators	Framatome- Pressurised Water Reactor (PWR)

4.2.3 EVENTS DIAGRAM

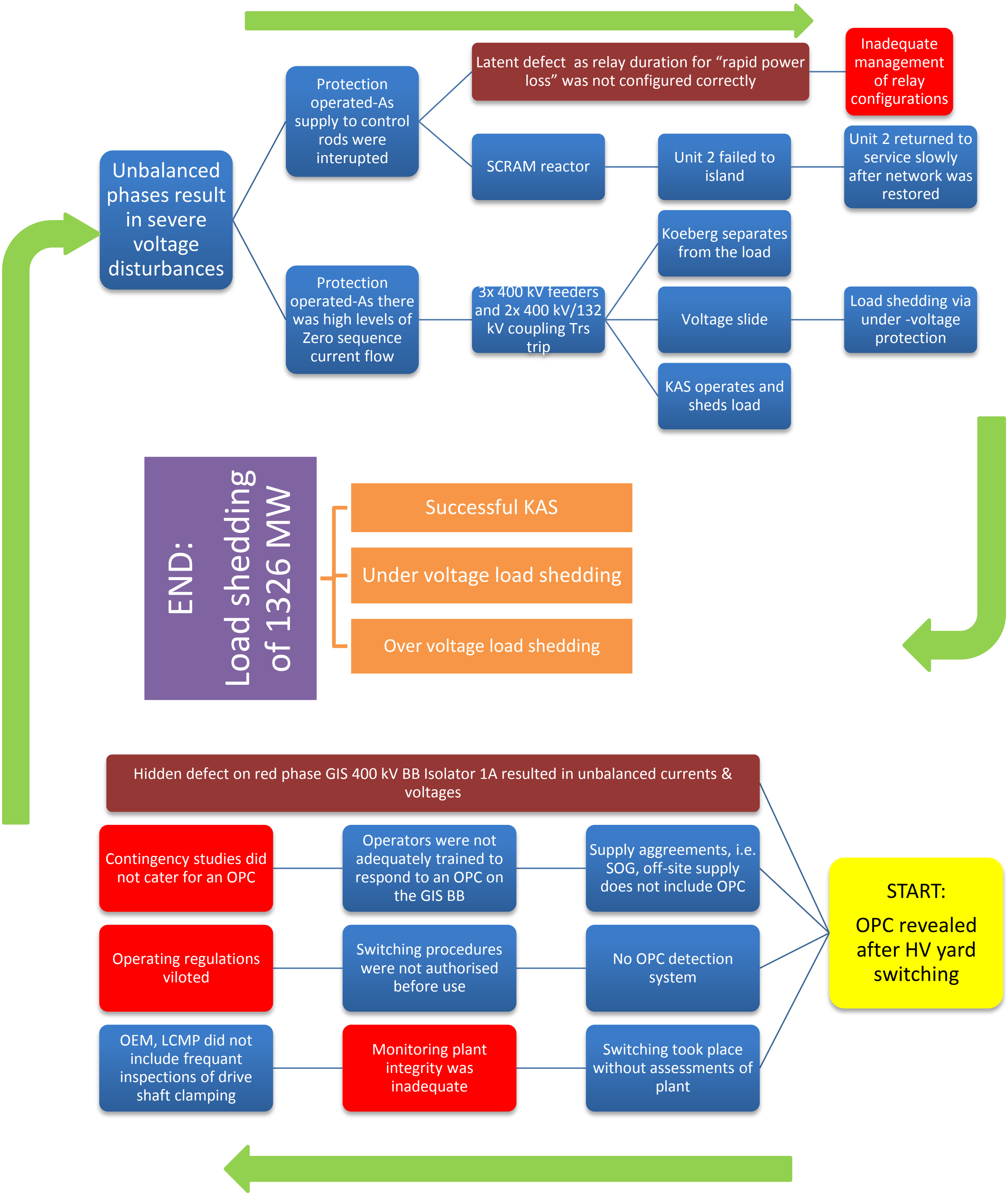


Figure 4-6 Diagram of the flow of 11 Nov 2005 events

4.2.4 CAUSE OF OPC

The Open phase condition occurred due to the switching taking place in the 400 kV GIS switchyard that revealed a latent defect on the red phase isolator on the 400 kV Bus section 1A. The latent defect occurred because there was an open circuit in the isolator terminals of that phase, due to deformation of the isolator material [33] and the shaft was displaced out of its housing. The following also contributed to the root cause:

- Monitoring of the plant integrity was inadequate
- Operating regulations were violated
- Contingency plans did not cater for an OPC
- Inadequate management of relay software configurations

Koeberg Unit 2 did not island from the 400 kV busbar. This occurred as the direct cause of the unit trip was due to the protection relays for “rapid power loss” not being configured correctly. KNPS should have been able to withstand a 30 % drop in voltage for a duration of 2.5 s [2], this was not so. During commissioning a latent defect occurred, where the relay’s circuit was incorrectly set to trip for voltage or current dips, where the duration of the interruption of supply (IOS) was not set, see Table 4-2 for the event summary. After every refuelling, the islanding procedure should be tested. By implementing this procedure, the performance of islanding could be improved.

Table 4-2 Koeberg Unit 2 OPC event at a glance

Cause of the single OPC	**Root cause**	**Contributing cause**
400 kV BB No1 red phase Bus section 1A isolator	Isolator shaft displacement	- Design Vulnerability in Protection scheme - Monitoring of the plant integrity was inadequate - Operating regulations were violated - Contingency plans did not cater for an OPC
Cause of the unit trip	**Root cause**	**Contributing cause**
“Rapid power loss” relays incorrectly set to trip for Voltage and current dips, irrespective of IOS duration	Commisioning defect	- Inadequate management of configuration

4.3 CORRECTIVE ACTIONS

In order to reduce the likelihood of these defects, the following should be considered:

- Prior assessments of the plant should be done prior to any switching and commissioning taking place on site.
- Only the latest revision and authorised commissioning procedures are allowed to be used.
- Contingency plans should cater for an open phase event.
- A management process should be put in place to monitor which configurations have been implemented on site.
- Frequent operator training to promptly diagnose and respond to an Open phase condition.

4.4 SUMMARY

After the OPC event at Koeberg NPP in November 2005, various internal and external investigations took place. The event occurred more than 12 years ago. And most of transmission and Nuclear generation i.e. System operator staff were aware and involved in analysing the event. This event revealed latent defects that were present in the plant, without anyone's knowledge. Corrective actions such as prior assessment of the plant and using authorised procedures could have assisted in detecting this condition.

CHAPTER 5 SURVEY AND AWARENESS

5.1 INTRODUCTION

In the following chapter the awareness of the staff working in relation to the nuclear plant will be analysed using a survey. This qualitative data comprises of a population of 150 people who were requested within Eskom Holdings, System operator to complete the survey. They were selected solely based on their working connection to either transmission substations and/or the Koeberg NPP. A sample size of 30 % was expected for the response to the survey, which will provide a 95 % confidence level. A minimum of 30 % was expected, as people often do not respond to surveys due to work load, lack of interest or lack of understanding of the topic. The real reasons to the low response rate are unknown.

5.2 FIELD RESEARCH

A survey was carried out to assess the current awareness of the condition. The awareness responses were analysed to assess if the relevant people are still knowledgeable about the topic. It was decided to assess the awareness of TX and Nuclear GX divisions only, as these two divisions are directly affected. A survey of 20 questions was compiled based on 4 main sections i.e. A: Personal information, B: OPC Awareness, C: Design vulnerability and D: International Operating experience. The full survey is shown in Appendix A4. This survey was voluntary and anonymous and the information will be used to gauge the understanding and perception of people in the system operator. It should be mentioned that the results of the survey may not be the view of Eskom as an organization.

The survey was sent to 150 Eskom system operator staff members, of which 34 are from the NPP and 116 are from the TX division. As the survey was voluntary only 32.4 % (11) responded from the Nuclear NPP and 31.1 % (36) responded from transmission. A total of 31.4 % (47) participants responded in total, this was deemed an acceptable sample of staff members. Based on the standard deviation of 1.24, margin of error of 0.5 and a confidence level of 95 %, the minimum acceptable number is 16 % (24) responses. Nonetheless, the number of responses was still low and a 99 % confidence level would have provided a more accurate reflection of the awareness of the population.

In Appendix A4, section A of the survey was included to ascertain some of the personal information about the participants. This information also assisted in comparing the awareness data from GX: Generation – the NPP and TX: Transmission – the substation staff.

Section B in the survey was to gauge the awareness of the OPC. These questions were posed to determine if the participants were aware that an OPC could occur in the NPP as well as in the TX substation, referring to questions 5 and 6 respectively (see Appendix A5). Question 7 was asking specifically regarding the awareness of the KNPS OPC event that took place in November 2005. Partial agreement answers were used to indicate if they: 1 – Strongly disagree, 2 – Disagree, 3 – Neutral, 4 – Agree or 5 – Strongly agree with the statement posed.

The questions in section C were regarding the awareness of the design vulnerability. These questions were to gauge if people in the system operator, in their opinion thought that either the NPP or the TX substation was vulnerable to this condition.

And lastly the questions in section D were regarding the awareness of the International Operating experience. Question 14 is very important, as it is an indication of how the person rates his/her own knowledge level regarding this topic.

It is expected that a low percentage of people are aware of the Open phase condition, due to many factors, such as people's exposure to this condition, the fact that an OPC occurred more than 10 years ago in South Africa, etc.

The other questions were to gauge if people in the system operator, were aware of the other OPC events that took place around the world and the learnings that came from the OE. Awareness of detection and mitigation methods was also asked to assess if people have knowledge of the methods that can be used to detect the OPC. Open ended questions were incorporated to allow the participants an opportunity to add comments.

Disclaimer: It must be noted that the outcome and results of the survey do not reflect the views of Eskom Holdings as an organisation.

5.3 RESULTS ANALYSIS

The analysis will be displaying the percentages of the total system operator and then analysing the percentages of each division. As each participant could only provide one answer per question, hence the percentages were calculated based on the "row %" across both divisions for the total values. One or two questions will be represented under sections B, C and D, with the remaining question responses (including Section A: Personal Information) displayed in the appendix A5. In the analysis below, the partial agreement answers (i.e. 1 – Strongly Disagree, 2 – Disagree, 3 – Neutral, 4 – Agree or 5 – Strongly Agree), as can be seen in the legends of the Figure 5-1, Figure 5-2, Figure 5-3 and Figure 5-4, with the associated colour. It will be assumed that a neutral selection indicates a lack of knowledge.

5.3.1 SECTION B: OPC AWARENESS

- ***Q7 – I was aware of the OPC that occurred in KNPS in Nov 2005***

In response to the above statement of question 7, a total of 61.7 % (neutral, disagree, strongly disagree) (see Figure 5-1) of the participants indicated that they were not aware of the open phase event that took place at Koeberg Power station in 2005, while only 38.3 % agreed or strongly agreed that they were aware. It can be deduced that the information surrounding this event was shared initially, but the information is not readily available to people and hence there is little awareness of the condition.

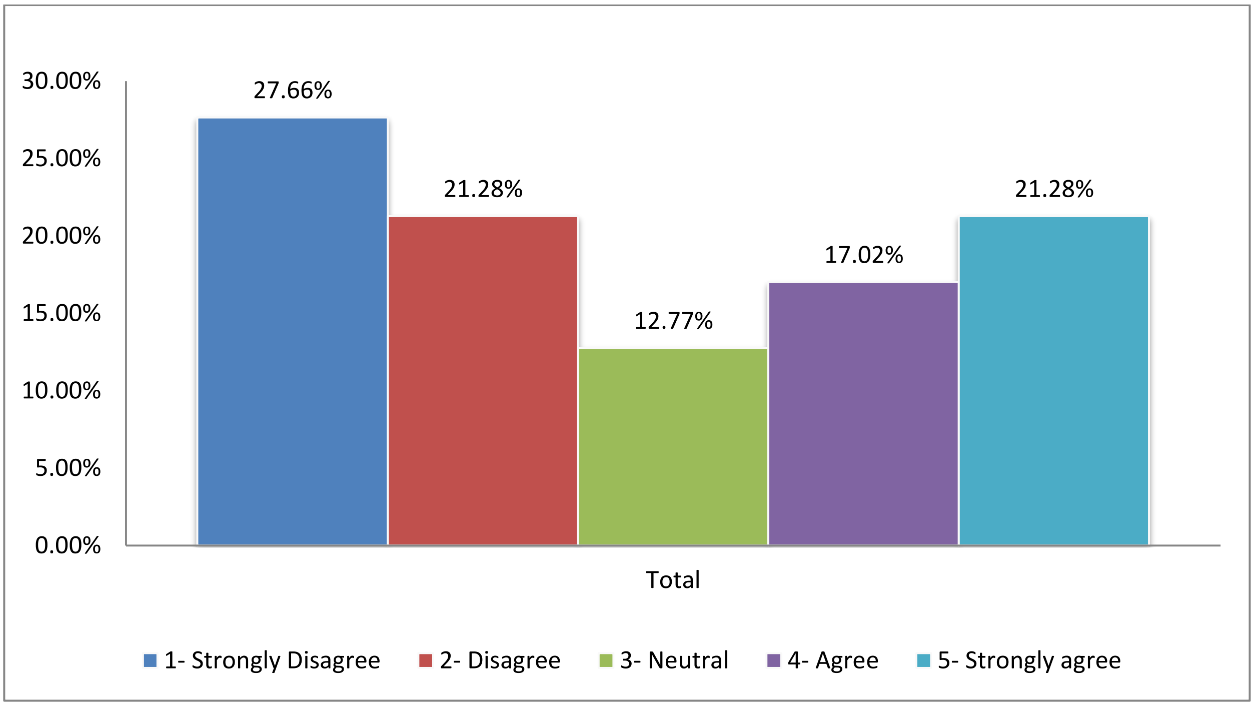


Figure 5-1 Q7 – Awareness total of KNPS OPC Nov 2005

Table 5-1 shows the awareness analysis of the KNPS OPC event that occurred in 2005. This analysis shows that the majority of GX staff at 36.36 % strongly agreed that they were aware of the KNPS OPC event and the second highest is 30.56 % of TX staff who strongly disagreed, meaning that they were not aware of this event.

Table 5-1 Q7 – GX vs TX awareness of KNPS OPC Nov 2005

Row Labels	1- Strongly Disagree	2- Disagree	3- Neutral	4- Agree	5- Strongly agree	Grand Total
GX	18.18 %	27.27 %	9.09 %	9.09 %	36.36 %	100.00 %
TX	30.56 %	19.44 %	13.89 %	19.44 %	16.67 %	100.00 %
Grand Total	**27.66 %**	**21.28 %**	**12.77 %**	**17.02 %**	**21.28 %**	**100.00 %**

5.3.2 SECTION C: DESIGN VULNERABILITY

- ***Q8 – In my opinion KNPS is vulnerable to the OPC***

In this section response to question 8 from the survey is graphically shown. It shows that the participants think that KNPS is vulnerable to the OPC. Collectively 46.81 % felt that KNPS is vulnerable, while 17.02 % of the participants felt that the NPP is not vulnerable to this condition. A big percentage of the participants (36.17 %) was neutral on the topic, indicating that they neither agreed nor disagreed (see Figure 5-2).

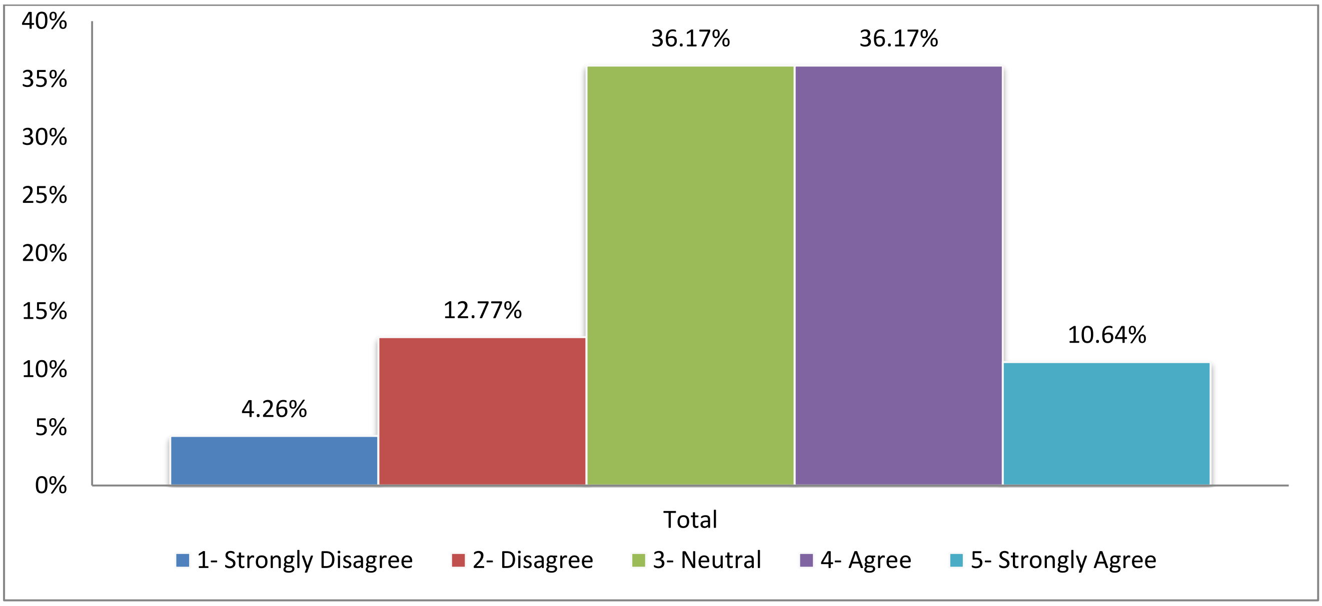


Figure 5-2 Q8 – KNPS is vulnerable to OPC

Table 5-2 shows the participants' opinion regarding the vulnerability of KNPS to this condition. This analysis shows that the majority of GX staff at 45.45 % agreed that they thought Koeberg was vulnerable and the second highest is 38.89 % of TX staff who were neutral, meaning they didn't know if Koeberg was vulnerable or not.

Table 5-2 Q8 – GX vs TX opinion that KNPS is vulnerable to OPC

Row Labels	1- Strongly Disagree	2- Disagree	3- Neutral	4- Agree	5- Strongly Agree	Grand Total
GX	0.00 %	9.09 %	27.27 %	45.45 %	18.18 %	100.00 %
TX	5.56 %	13.89 %	38.89 %	33.33 %	8.33 %	100.00 %
Grand Total	**4.26 %**	**12.77 %**	**36.17 %**	**36.17 %**	**10.64 %**	**100.00 %**

5.3.3 SECTION D: INTERNATIONAL OPERATING EXPERIENCE

- ***Q14 – I am very knowledgeable about the effects of an OPC***

The results of question 14 are an important measurement, as it is an indication if people rate themselves as being knowledgeable of the OPC or not. Collectively 78.73 % rated themselves as not being knowledgeable of this topic or being neutral, which confirms expectations. A smaller proportion being 21.28 % stated that they agreed (19.15 %) or strongly agreed (2.13 %) that they were knowledgeable of this topic (see Figure 5-3).

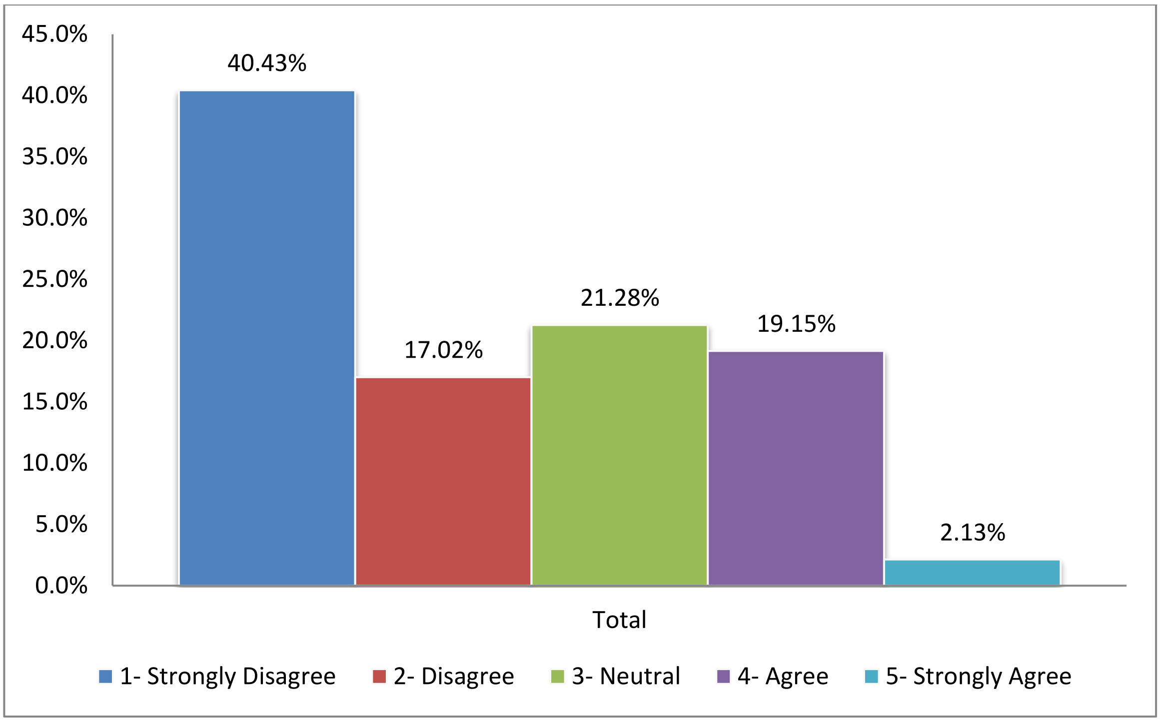


Figure 5-3 Q14 – Total Knowledgeablility of OPC effects

Table 5-3 shows the participants' opinion regarding their knowledgeability of this condition and its effects. This analysis shows the majority at 44.44 % is TX staff who strongly disagreed, meaning that they were not at all knowledgeable of the topic and that the second highest is the GX staff at 36.36 % who were neutral meaning that they didn't know much about this condition.

Table 5-3 Q14 – GX vs TX Knowledgeable of OPC

Row Labels	1- Strongly Disagree	2- Disagree	3- Neutral	4- Agree	5- Strongly Agree	Grand Total
GX	27.27 %	18.18 %	36.36 %	18.18 %	0.00 %	100.0 %
TX	44.44 %	16.67 %	16.67 %	19.44 %	2.78 %	100.0 %
Grand Total	**40.43 %**	**17.02 %**	**21.28 %**	**19.15 %**	**2.13 %**	**100.0 %**

- ***Q16 – I was aware of other OPCs that occurred in the world***

For the question above, the participants collectively responded by indicating that more than 74.47 % (neutral, disagree, strongly disagree) did not know about other OPCs that occurred elsewhere in the world. This indicates that the international operational experience is not well distributed within the system operator (see Figure 5-4).

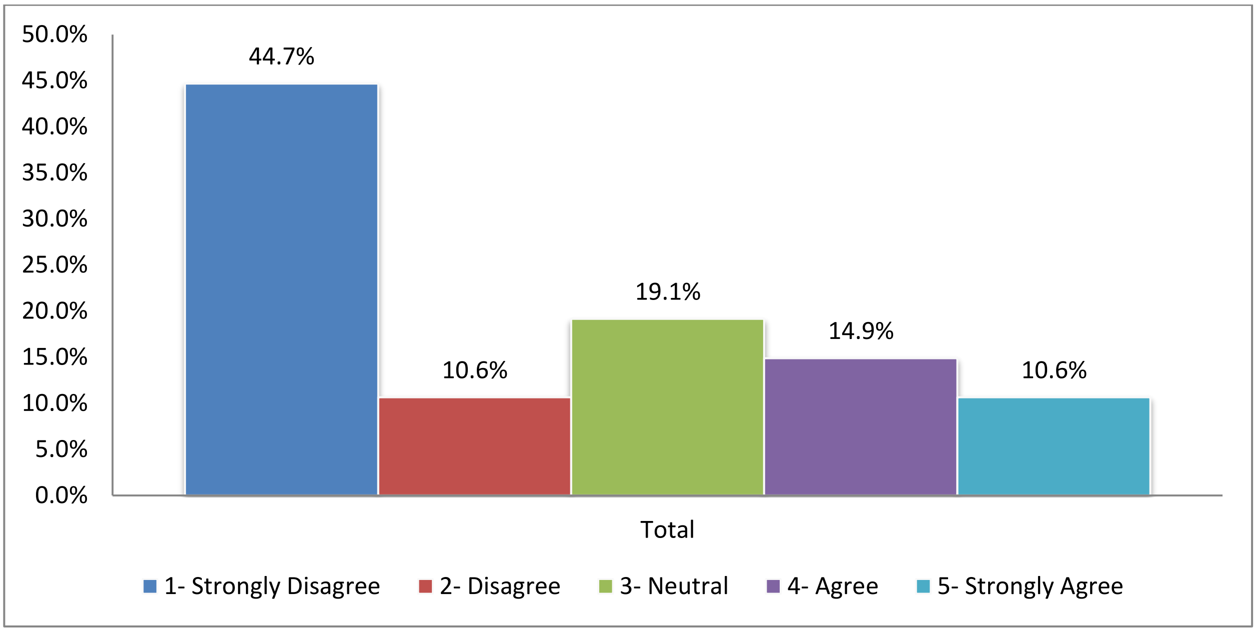


Figure 5-4 Q16 – Awareness of international OPC OE

Table 5-4 shows the participants' awareness regarding their knowledgeability of international OPC operating experience. This analysis shows that the majority at 52.78 % from TX staff strongly disagreed, meaning that they were not aware of International OE. The second highest amongst GX staff at 27.27 % in each category who disagreed and strongly agreed meaning that there is the same proportion of staff who were aware of the other OPC events that occurred around the world and those who did not know about it.

Table 5-4 Q16 – GX vs TX Awareness of international OPC OE

	1- Strongly Disagree	2- Disagree	3- Neutral	4- Agree	5- Strongly Agree	Grand Total
GX	18.18 %	27.27 %	9.09 %	18.18 %	27.27 %	100.00 %
TX	52.78 %	5.56 %	22.22 %	13.89 %	5.56 %	100.00 %
Grand Total	**44.68 %**	**10.64 %**	**19.15 %**	**14.89 %**	**10.64 %**	**100.00 %**

5.4 SUMMARY

Based on the field research using an OPC awareness survey, it was revealed that overall people are aware that an OPC could occur in a nuclear plant. A majority at 36.36 % of generation staff was aware of the Koeberg OPC event that occurred in 2005, where the majority at 30.56 % of the transmission participants were not aware of this event. The survey analysis revealed that over 40 % of the participants stated that they were not knowledgeable of this topic. The results demonstrate that there is insufficient overall knowledge and understanding of this condition within the system operator.

The two main focus areas are international operating experience and the effects of the open phase condition, which require the most attention. Through bi-annual training sessions with staff from generation and transmission, their knowledge of this phenomenon can be improved and it will provide a platform for them to get to know each other better and to share their experiences.

CHAPTER 6 OPC DETECTION AND MITIGATION METHODS

6.1 INTRODUCTION

The detection and mitigation of the Open phase condition is of paramount importance. The events outlined in chapter 3 have shown that equipment can get damaged. The safety equipment and buses can get compromised and may not operate as per the design. These events also illustrate the vulnerability that currently exists, where the installed protection relays and instruments do not have the capability to separate the faulty section of the system from the healthy sections in an OPC.

6.2 DETECTION AND MITIGATION

The definition of “detection” according to the Oxford Dictionary is “the action or process of identifying the presence of something concealed.” [43]

The definition of “mitigation” according to the Oxford Dictionary is “the action of reducing the severity, seriousness of something” [44]. Mitigation has to do with decreasing or lessening the effects of the OPC.

The objective of detection methods is to reveal, discover and uncover an open phase under all conditions (cases 1-4) (see Figure 6-1). Additional variances of cases 2 and 3 are the insertion of resistances in the ground faults in addition to testing solid ground faults. Due to the design vulnerability, the existing protection was not designed to detect an OPC. And from the case studies it can be clearly illustrated that this vulnerability affects the safety of buses, equipment important-to-safety and the offsite supply.

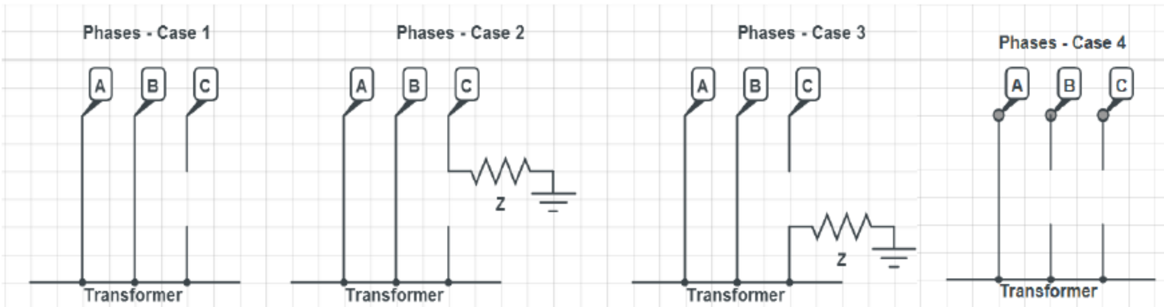


Figure 6-1 Various Open phase conditions [45] [46]

The authors in [45] used various simulation techniques, as mentioned in section 2.7 MODELING. From their simulations they found that the different transformer topologies affect the response to the OPC. Hence the quantity of zero and negative sequence current produced during an OPC is dependent on the construction of the transformer.

From their results, it can be seen that only using voltage surveillance would not detect the OPC during lightly loaded configurations. Either detection methods using the current from the primary circuit in lightly loaded conditions will require zero sequence detection or in heavily loaded conditions it will require negative sequence detection. An additional detection method to the loading application is necessary, which is to detect if one of the three phases’ line current is lost.

6.3 DETECTION AND MITIGATION METHODS

The OPC IAEA safety report states that the measuring philosophy used in the protection needs to be taken into consideration, such as phase to phase, phase to earth, which phases are measured and which not, symmetrical components, and if there is coincident logic, e.g. 2 out of 2 or similar. For permanent corrective solutions on either the HV or LV side of the transformer, one or more of the following parameters should be measured:

- Negative sequence voltages and currents
- Zero sequence voltages and currents
- Magnetisation current
- Current injection
- Phase to phase voltage
- Phase to earth voltage

  - For a transformer with no load or in standby:

An alarm should be activated showing that there is an OPC in the offsite power supply. An OPC in this case would not have a negative effect on downstream equipment and operators have sufficient time to assess and respond to the event.

  - For an in-service transformer which is carrying load:

An alarm should be activated showing that there is an OPC in the offsite power supply. Dependant on the plant design basis, the response time will be evaluated. The outcome will determine if manual operator intervention will be fast enough or if automatic separation is required to prevent damage to important safety equipment.

The following sections will outline the methods of protection needed on the HV and LV side of the transformer as well as diagnostic measures that can detect an OPC.

6.3.1 HV SIDE OF TRANSFORMERS

6.3.1.1 ZERO SEQUENCE CURRENT

The zero-sequence current component is zero in a perfectly balanced system, but in the field, it is greater than zero because the network is not perfectly balanced. In transformers which are solidly earthed, the zero sequence – earth fault current caused by an OPC can be detected [2]. This sequence component is affected by transformer loading and cannot detect all possible OPC events. In lightly loaded conditions, as the pick-up setting is small enough so it can detect a single OPC, yet high enough to prevent spurious pickups. This protection can be set to indicate an alarm. And further action can be taken from there.

6.3.1.2 MAGNETIZING CURRENT

It is generally challenging to detect an OPC, especially in an unloaded or lightly loaded transformer. Hence the transformer's magnetizing current can be used to detect an OPC. The general range for the magnetizing current in unloaded transformers is from 50-150mA. The magnetizing current in the green phase (I_{L1}) that is present before an OPC occurs (see Figure 6-2 left), is not present after (see Figure 6-2 right) an OPC has occurred on the

HV side of a transformer. Figure 6-2 right, shows the change in magnitudes of the red (I_{L3}) and blue (I_{L2}) phase currents and that there is no current flowing in the green phase.

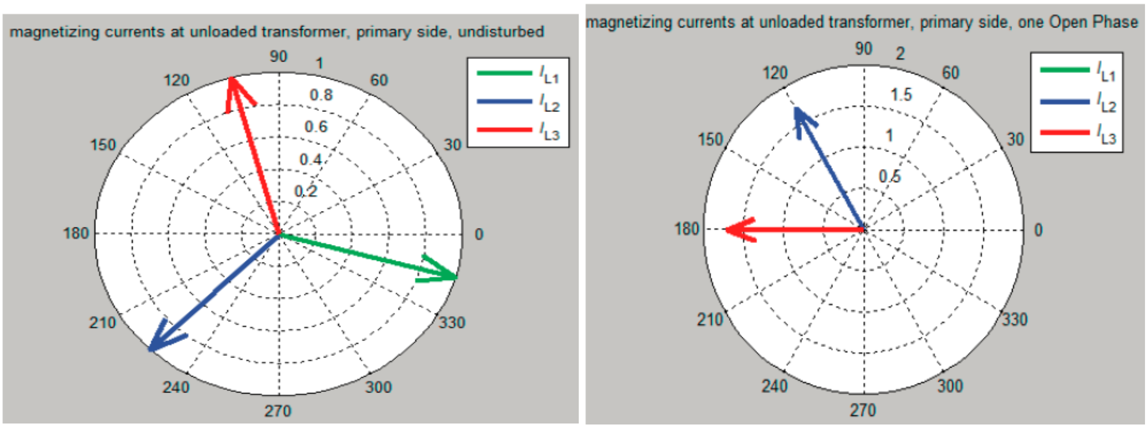


Figure 6-2 Magnetizing current before (left), after (right) OPC HV side of unloaded Tr [2]

This current range can be detected by Optical current transformers (OCT) installed on the HV transformer bushings. A comparative protection relay can be used to check the difference between normal magnetizing current and the OPC magnetizing current. An alarm is acceptable, as the transformer is unloaded. After evaluation using an IEC 61850 process bus and OCT, it was found that an open phase can be detected. The tests were done on Star-Star, Star-Delta and Delta-Star transformers [47].

6.3.1.3 INJECTION ON STAR POINT

Injecting a signal into the star point of the transformer can also be used as an active OPC detection method. The current flow can then be monitored as it flows on the HV side of the transformer. The system used for injecting current consists of an AC source with its own frequency, current transformer, measuring probe and electronic controller [2]. This method detects the zero sequence impedance. Normally, in a healthy system the impedance ranges from hundreds to thousands of ohms. When an OPC occurs the impedance can increase to mega-ohms and consequently the AC source current decreases. This detection method is a good method to use if the transformer is lightly or not loaded.

6.3.1.4 ADVANCED MICROPROCESSOR

By using an advanced microprocessor, algorithm statements were developed to detect an OPC. Using simulations and modelling, the IAEA presented the following three algorithm statements:

1. When an OPC occurs and there is a path to earth and the zero sequence current is greater than a set calculated value.
2. When an OPC occurs and there is no path to earth and the current on one phase reduces to zero; the zero and negative sequence current set points are used to prevent tripping for faults downstream.
3. When a double OPC occurs without a path to earth, both phase currents will reduce to zero.

By implementing 'OR' logic gates, a trip will only activate according to "one-out-of-three" logic. This detection method cannot be used on all transformer configurations and applicability must be assessed using analytical models [2].

6.3.2 LV SIDE OF TRANSFORMERS

6.3.2.1 PHASE TO PHASE UNDER-VOLTAGE

This detection method can be installed on the buses that feed the station house load. By implementing the "one-out-of-three" logic philosophy, when the relay senses an under-voltage then the circuit breakers feeding the house load buses will trip and the alternate AC supply will energise those buses. Based on simulation results, a nominal voltage set point of 85 % was selected, with a 12s time delay to differentiate it from the rest of the protection relays. This method can detect OPC on the offsite power supplies [2].

6.3.2.2 NEGATIVE SEQUENCE VOLTAGE

The negative-sequence voltage component is zero in a perfectly balanced system, but in the field, it is greater than zero because of unbalanced components in the transformer. This detection method should be installed at several places in the plant, at varying voltage levels. Time delays need to be implemented, to trip faster at higher voltages and slower at lower voltages [2]. This is to ensure that the fault is picked up and isolated as close as possible to the location where it occurs.

According to an Eskom Standard [48], if the loads that are connected to a generator are unbalanced, negative phase sequence (NPS) currents are produced. This current produces a stator MMF, which is at the same speed but in the opposite direction to the rotor. The effect of this MMF causes heat and eventually damage to the generator rotor [48]. As mentioned before OPCs cause NPS currents, when there is an open circuit on the phase conductor or breaker that does not close, etc. The NPS protection has to encapsulate three characteristics, i.e. "one thermal characteristic and two definite time characteristics" [48]. The negative phase sequence protection for a generator with a generator circuit breaker and one without, are shown in Figure 6-3 and Figure 6-4.

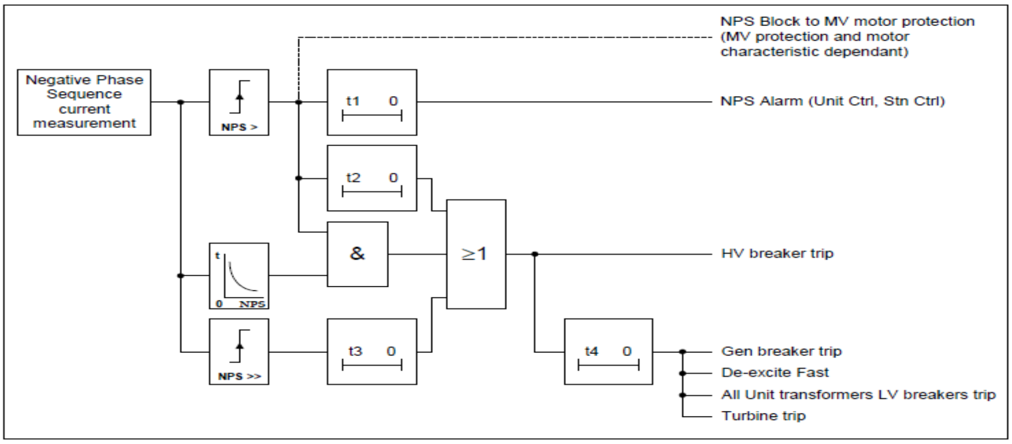


Figure 6-3 Generator with circuit breaker NPS logic diagram [48]

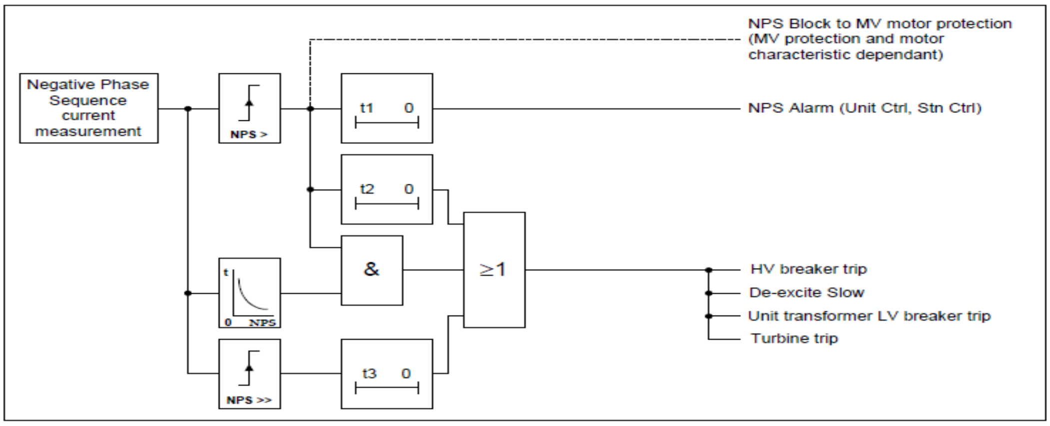


Figure 6-4 Generator without circuit breaker NPS logic diagram [48]

6.3.3 ANALYTICAL MEASURES

6.3.3.1 VIBRATION MEASUREMENTS

As stated in section 2.3, vibration is one of the effects of an OPC. As the negative sequence voltage induces oscillation on the motor shaft and this causes an induction motor to vibrate. An instrument that measures the vibrations can be used on many motors concurrently.

6.3.3.2 BATTERY CHARGES

Another method for detecting an OPC is by using the alarms that are installed on the battery chargers. If an OPC occurs and the trigger points are exceeded, the functionality must be turned off in order to safeguard the charger [2]. The alarm can be used to indicate to controllers that there is a problem, but protection relays will still be required to separate the unhealthy section.

6.4 SUMMARY

There are various types of detection methods currently available, each focusing on a different aspect of an Open phase condition. Most of these methods should not be implemented in isolation, as a combination of methods will provide the best solution to detect majority of the OPC events on the HV and LV sides of the transformer, especially if it is lightly loaded. These methods must be integrated into the existing protection scheme and grading settings must be revised to provide optimum protection.

CHAPTER 7 CONCLUSION AND RECOMMENDATIONS

The research question is: "**Is it possible to prevent or mitigate an Open phase condition from occurring in the switchyard of a nuclear power plant?"** Based on the case studies of the various Open phase events, it can be deduced that the answer is "No"; it is not possible to prevent an OPC from occurring. This is due to many unforeseen circumstances that could occur in the plant, which might not be possible to prevent.

It is however possible to ensure that the likelihood and severity of an OPC occurring in a NPP are kept very low. This can be achieved by the implementation of several of the recommendations.

The operators and licensees still have the responsibility to continually assess their own nuclear power plants and the switchyard to address any design vulnerability issues that exist.

It can be concluded that there is insufficient overall knowledge and understanding of this condition within the system operator. The two main focus areas that require the most attention are international operating experience and the effects of the open phase condition. Educating the system operator through training has the potential to strengthen the relationship between transmission and the nuclear plant within Eskom holdings.

It is recommended that the following can be implemented in each nuclear plant, to increase the OPC knowledge level, response and detection:

- Combined bi-annual OPC training sessions for staff from generation and transmission divisions.
- Quarterly workshops- to provide a platform for them to get to know each other better and to share their experiences.
- Each nuclear plant should simulate all possible OPCs on their plant with the existing protection.
- When design vulnerabilities exist, they must investigate via simulations which OPC protection relays would work best for their plant configuration.
- Where non-compliance to regulations exists, subject matter experts should be consulted to provide advice on how compliance can be regained.
- The new OPC protection should be integrated into the existing network and settings revisions could be required, to avoid spurious trips.
- All procedures, maintenance documents, contingency plans, etc. should be revised regularly and the Open phase condition should be incorporated.
- Plant operators should be required to frequently walk through the HV switchyard to visually assess the state of the HV equipment and all connection points, using specialised cameras such as an Infra-Red camera.
- The unbalanced withstand capability of the nuclear plant's electrical systems and safety equipment should be assessed to be within specification.
- Quality process should be put in place, to ensure good workmanship during commissioning of new equipment and maintenance.
- Operators should be regularly trained and briefed on how to recognise the symptoms and effects on equipment when an OPC occurs.
- New protection relays should be installed in the plant, to detect and alarm when an OPC is present.
- There should be a combination of information available from different equipment i.e. alarms, trips, vibration measurements, temperature readings, individual phase voltages indications, etc.

- Operator manuals and procedures should be updated, to provide clear steps for operators to follow in response to an OPC i.e. voltage readings, motor trips, battery charger trips, etc.
- The best solution might be both detection protection on the HV and LV side of all transformers, where needed.
- According to defense in depth, separation from only the defective power supply is necessary.

Preparing for the prevention on an Open phase will result in drastically decreasing the likelihood of this condition occurring in the plant, even though unforeseen events can’t be prevented from occurring.

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APPENDIX

A1 TRANSFORMER WINDING DESIGNS

A1-1 TWO WINDING, STAR - STAR SHELL FORM

In Figure A- 1, each phase is entirely surrounded by core steel. Shell type transformers are usually used as power transformers greater than 200MVA. This type is preferred for large generator step-ups and in TX substations, because they are more durable and have a higher through-fault withstand capability.

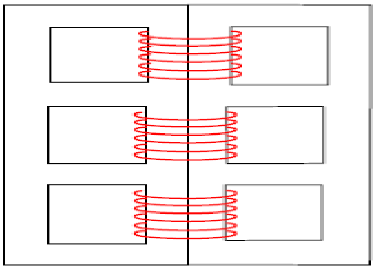


Figure A- 1 Two winding Star - Star Shell transformer [19]

A1-2 TWO WINDING, STAR - STAR, FIVE LEGGED FORM

Figure A- 2 shows the type of transformer which is used in underground systems, as pad-mount transformers or on overhead systems as platform- mounted. The core can be four wound cores with the cross-sectional area carrying half the flux. The two inner cores have a longer magnetic path than the two outer cores.

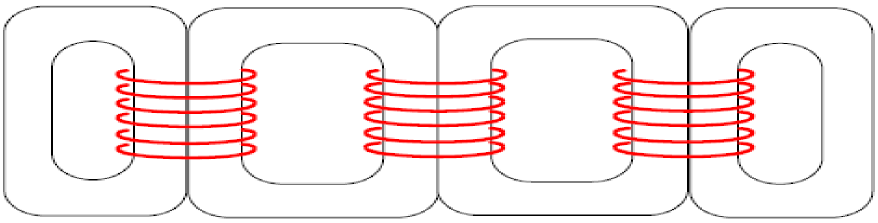


Figure A- 2 Two winding Star - Star 5 legged transformer [19]

A1-3 TWO WINDING, DELTA- STAR, THREE LEGGED FORM

In Figure A- 3 and Figure A- 4 the delta winding is on the primary side of transformer, where the open phase is simulated to be.

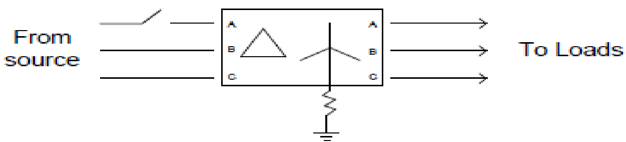


Figure A- 3 Two winding, Delta- Star, three legged form [19]

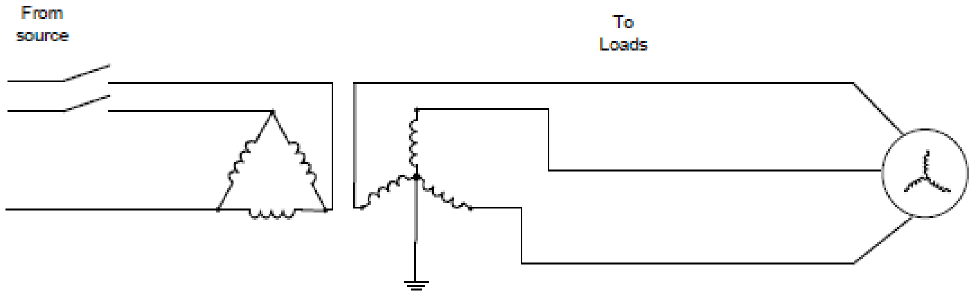


Figure A- 4 Two winding, Delta- Star, three legged form [20]

A1-4 TWO WINDING, STAR - DELTA, THREE LEGGED FORM

In Figure A- 5 and Figure A- 6, the star winding is on the primary side of transformer, where the open phase is simulated to be.

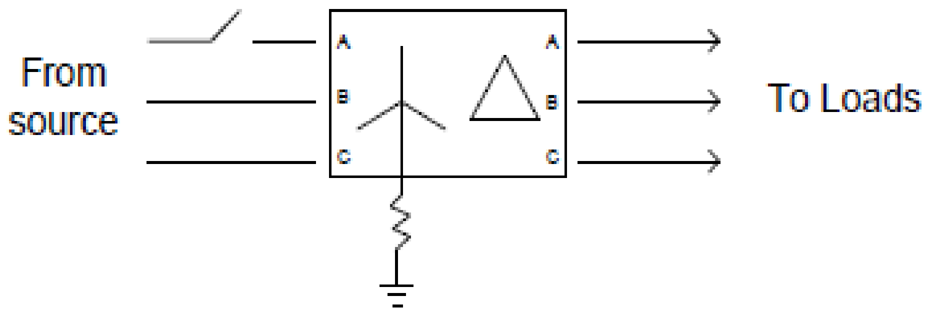


Figure A- 5 Two winding, Star - Delta, three legged form [19]

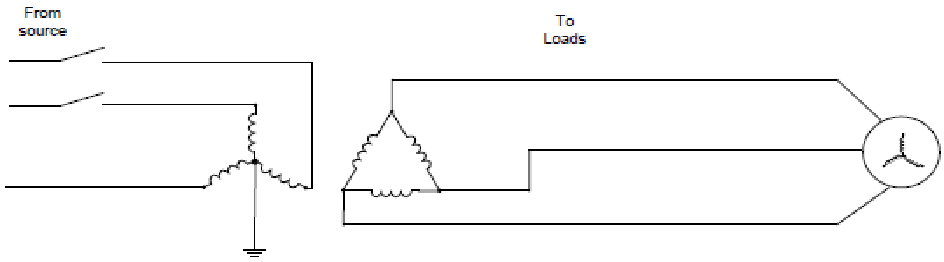


Figure A- 6 Two winding, Star - Delta, three legged form [20]

A1-5 THREE WINDING, STAR - STAR, SHELL WITH BURIED DELTA TERTIARY FORM

Same configuration as in Figure A- 1 Two winding, Star- Star shell form, with an additional buried delta tertiary winding. This tertiary winding has an effect on the zero sequence circuit. The buried delta is modelled with a corner ground.

A2 ADDITIONAL OPC CASE STUDIES

A2-1 BYRON UNIT 1, ILLINOIS, USA, 28 FEB 2012

- ***STATION LAYOUT***

BNPS Unit 1 has the same station layout as BNPS Unit 2, see section 0

- ***EVENT DETAILS***

On the 28th February 2012 at 17:30 at Byron Nuclear Power Station Unit 1 was operating at 100 % power output, when an Ohio Brass inverted porcelain insulator failed in the 345 kV switchyard, and the conductor fell to the ground. This was similar to the event that occurred in Byron Unit 2 in January 2012, a month earlier. This time it was the ‘A’ phase 345 kV insulator which failed, which held up one of the three electrical phases on an A-frame structure, energising the two SATs 141-1 and 141-2 of Unit 1. This was a mechanical failure and caused an Open phase condition on phase ‘A’, as well as a short circuit, which was a faulted condition. The mechanical failure took place between the insulator support A-frame structure and the isolator on Bus 6 to the SAT, see Figure A- 7. The difference in this event was that there was also a phase to earth fault on the switchyard side of the standby transformer and the fault current was sufficient to operate the protection [2]. Here the 4.16 kV Under-voltage protection on the ESF buses did sense the fault condition and automatically chopped over to the EDGs 1A and 1B, as designed.

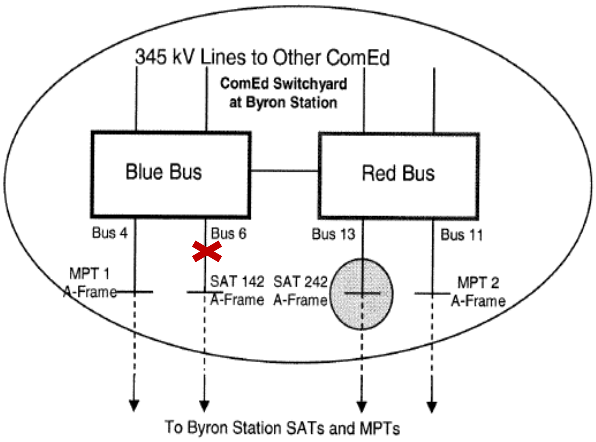


Figure A- 7 Byron Unit 2 SAT 142 [22]

The breakers on the SATs opened and the EDGs started up and energised the 4.16 kV ESF buses [22]. The 2A Auxiliary Feedwater (AF) pump started and the Steam Generators (S/Gs) were supplied with Feedwater (FW). An automatic start signal was not received by the 2B diesel driven AF pump. Operators decreased the reactor output to assist with the injection of cooler AF into the S/Gs.

The bays connected to the SATs 141-1 and 141-2 via the 6.9 kV buses and the bays connected via the non-ESF 4.16 kV buses were automatically transferred to the UATs. At the time of the trip, the 1B EDG was operating due to planned monthly surveillance and responded as designed by energising the 4.16 kV ESF bus 142 and hence the unit remained energised [22].

The operators responded appropriately with the “Abnormal Operating” procedures. At 17:36 the operations staff declared a NOUE for the “loss of offsite power (LOOP) to essential buses” for greater than 15 minutes

[22]. At 21:54 of the same day, the 4.16 kV ESF buses of Unit 1 were cross tied via the cross-tie breakers to the reserved offsite power, see Figure 3-3.

The repairs were completed almost 25 hours after the insulator failure and the station was normalised to the normal offsite power via the 4.16 kV ESF buses. The NOUE was terminated at 21:00 on the 29 February 2012. The OPC caused by the insulator failure resulted in a ground fault, unlike the OPC that occurred in January 2012, which was a non-faulted open circuit. The OPC on Unit 1 caused a loss of normal offsite supply, but the reactor Unit did not trip [22].

- ***CAUSE OF OPC***

The Open phase condition occurred due to an Ohio Brass inverted porcelain 345 kV insulator which failed. It failed in an insulator stack on the A-frame structure, which provided vertical support to the 'A' phase conductor of Unit 1 345 kV/6.9 kV station auxiliary transformer 141. There was "service propagation of a large manufacturing material defect that covered 25 % of the fracture cross-section", see Figure A- 8. The fracture was due to "poorly vitrified porcelain", the porosity had a high density and micro-cracks formed causing an internal mechanical failure. Additional insulator portions exhibited the same poor-quality porcelain as the one that failed [22].

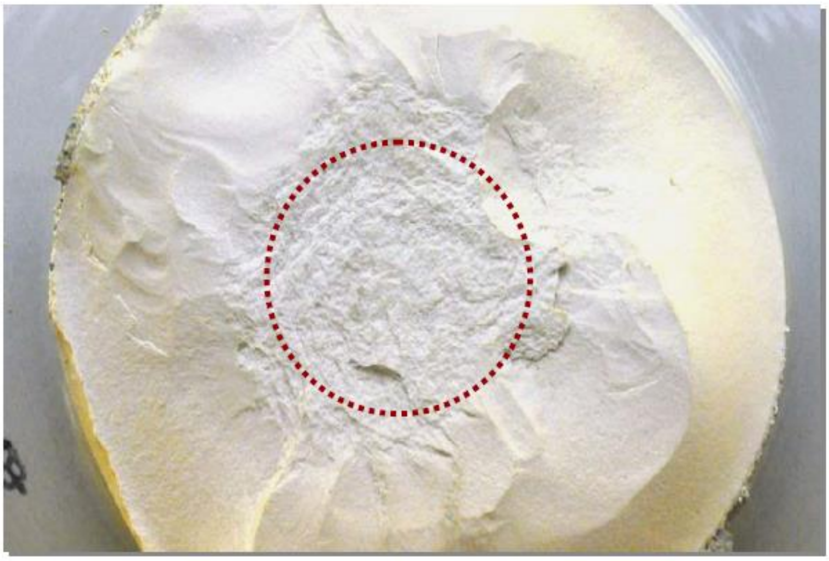


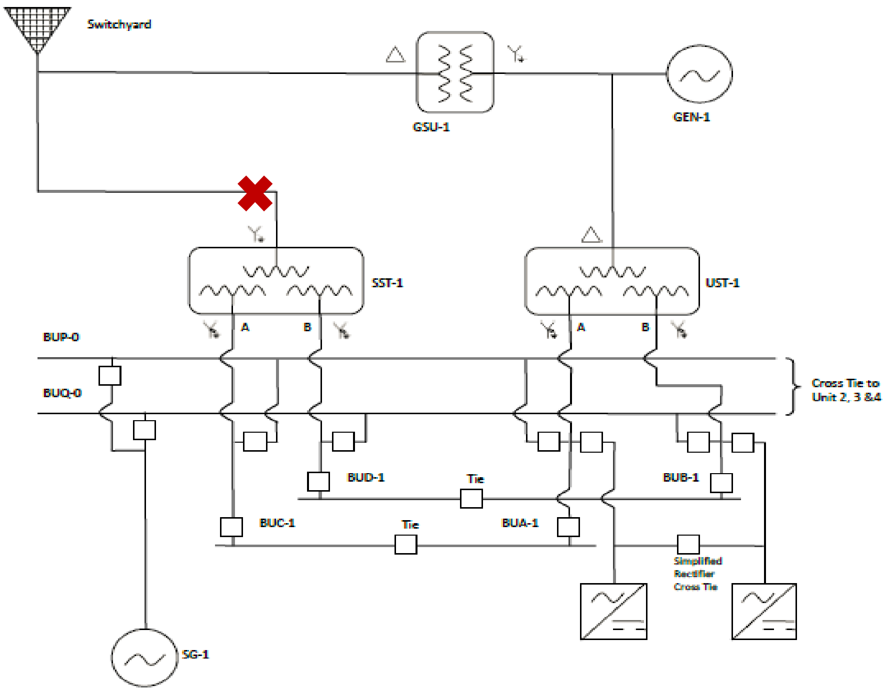
Figure A- 8 Byron Unit 1 failed insulator [25]

A2-2 BRUCE A UNIT 1, CANADA, 22 DEC 2012

- ***STATION LAYOUT***

The Bruce Power Generating Station (BPGS) is situated on the shores of Lake Huron, 250 km North-West of Toronto, Ontario which is in Canada. BPGS is privately owned by Ontario Power Generation (OPG) and it is the largest NPP in North America [49]. BPGS generates 20 % of Ontario's electric energy. The NPP has two generation stations, i.e. Bruce A and Bruce B. When fully operational, the whole plant will generate a total of 6232 MW (net) electricity [49]. In 1999 Ontario Hydro was split up into five divisions. One division is OPG, which runs all the power generation plants in Canada.

The Bruce A and Bruce B stations have four CANada Deuterium Uranium (CANDU) reactors each. CANDU plants are Pressurised Heavy Water Reactors (PHWR). The reactor units are cross tied to each other, see Figure A- 9. Each unit has its own Generator Service Transformer (GST), System Service Transformer (SST) and Unit Service Transformer (UST). The TX network connects to BPGS via two 500 kV lines to Milton and Longwood stations and three double circuit 230 kV lines to Kitchener, Orangeville and Owen Sound stations. The network TX capacity is 5000 MW [49]. A High-Resistance Open Phase (HIROP) protection scheme is installed in this power station.



Legend
GSU = Generator Service Transformer
SST = System Service Transformer
UST = Unit System Transformer

Figure A- 9 Bruce A Unit 1 layout [33]

- ***EVENT DETAILS***

On the 22nd December 2012, during a maintenance outage at Bruce A Unit 1 NPP the electrical protection operated and tripped the Maintenance Cooling System (MCS) pump. The MCS is equivalent to the PWR shutdown cooling system. The MCS pump trip caused an unbalanced voltage condition. After the MCS pump tripped, operators tried several times to restore the maintenance cooling, by switching in a standby MCS pump. The standby pump failed to operate for more than a few minutes, before tripping on electrical protection. They then declared a loss of maintenance cooling. There was sufficient time before the system reached excessive temperatures exceeding 90^0 C.

According to the World Association of Nuclear Operators (WANO) Significant Operating Experience Report (SOER), there were no other indications in the control room, to show that an Open phase condition had occurred. Hence, operators found it challenging to diagnose the cause of the trip. The System Service Transformer No1 (SST-1) did have open phase alarms installed. The alarming system on the SST-1 did not operate, as the conditions for an alarm were not fulfilled [33]. Even though there was an ungrounded Open phase condition in the 230 kV switchyard, the relay pick-up point was set higher than the unbalance produced by the OPC; hence the protection did not indicate any alarms for the HV ground fault. The protection only initiated an alarm 120 minutes after the initial MCS pump trip occurred, after two of the main boiler feed pumps were put in operation [33]. The operators then went to physically investigate the 230 kV electrical network outside. In the switchyard they discovered the OPC i.e. where a 230 kV jumper broke off. The connection at the base plate of the HV side of the SST to the jumper broke loose due to strong winds experienced in the area. The station loads were then fed from an alternate SST. The MCS was only restored 150 minutes after the first trip, meaning there was no shutdown cooling for that duration. During the lightly loaded condition due to the maintenance outage, the offsite source was in a degraded state [33].

Another factor that had an effect in this event is that the operating experience regarding the Open phase condition event that took place in Byron Unit 2 NPP (in Jan 2012) was not reviewed adequately. It was deemed not to be applicable to Bruce NPP. It was incorrectly determined to be safe from an OPC, as it had High Resistance Open Phase (HIROP) protection installed. Unfortunately, the HIROP protections' trigger settings were not verified to operate during low loading conditions, i.e. in the case of a Maintenance outage, etc.

- ***CAUSE OF OPC***

The Open Phase Condition (ungrounded) occurred due to strong winds at the transformer location which caused the 230 kV jumpers to break off at the HV side of the SST-1. It broke off due to excessive stress on the connection point to the welded plate. There was excessive stress, because it was found in the forensic investigation that the welded plate was not the correct design for the application it was used for [33].

A2-3 VANDELLOS UNIT 2, SPAIN, 9 AUG 2006

- ***STATION LAYOUT***

Vandellòs Nuclear power plant (VNPP) is situated in Vandellòs, on the Mediterranean Sea in Catalonia, Spain. The Nuclear plant had two Units. Unit one was a Carbon Dioxide gas cooled reactor (GCR) with an output of 508 MW. The Unit was decommissioned in 1990, soon after a fire broke out and damaged one of the Unit's turbo generators in 1989. Unit two is a 3 loop, Westinghouse Pressurised Water Reactor with an output of 1087 MW, which is a generation III reactor. The VNPP is owned by Endesa and Iberdrola, 72 % and 28 % respectively. The Mediterranean Sea water is used to cool down the reactor.

Figure A- 10 shows the various switchyards, i.e. 400 kV, 220 kV and 110 kV respectively. The 110 kV/6.25 kV/6.25 kV Reserve Auxiliary Transformer (TAR) has a Star-Star-Star with a buried Delta winding. The 21 kV/6.25 kV/6.25 kV Unit Auxiliary Transformer (TAU) has a Delta-Star-Star winding. There are 2 Diesel generators which are connected via the 6.25 kV busbar to either the TAR or TAU, in case of emergencies. A 220 kV/6.25 kV/6.25 kV External Auxiliary Transformer (TAE) energises the 220 kV switchyard, which also has a Star-Star-Star with a buried Delta winding. The 400 kV switchyard is supplied by the 21 kV/400 kV Main Transformer (TP) which has a Delta- Star winding, with three separate phase transformers, i.e. one transformer for each of the 'R', 'S' and 'T' phases. The buried Delta winding voltages were not provided.

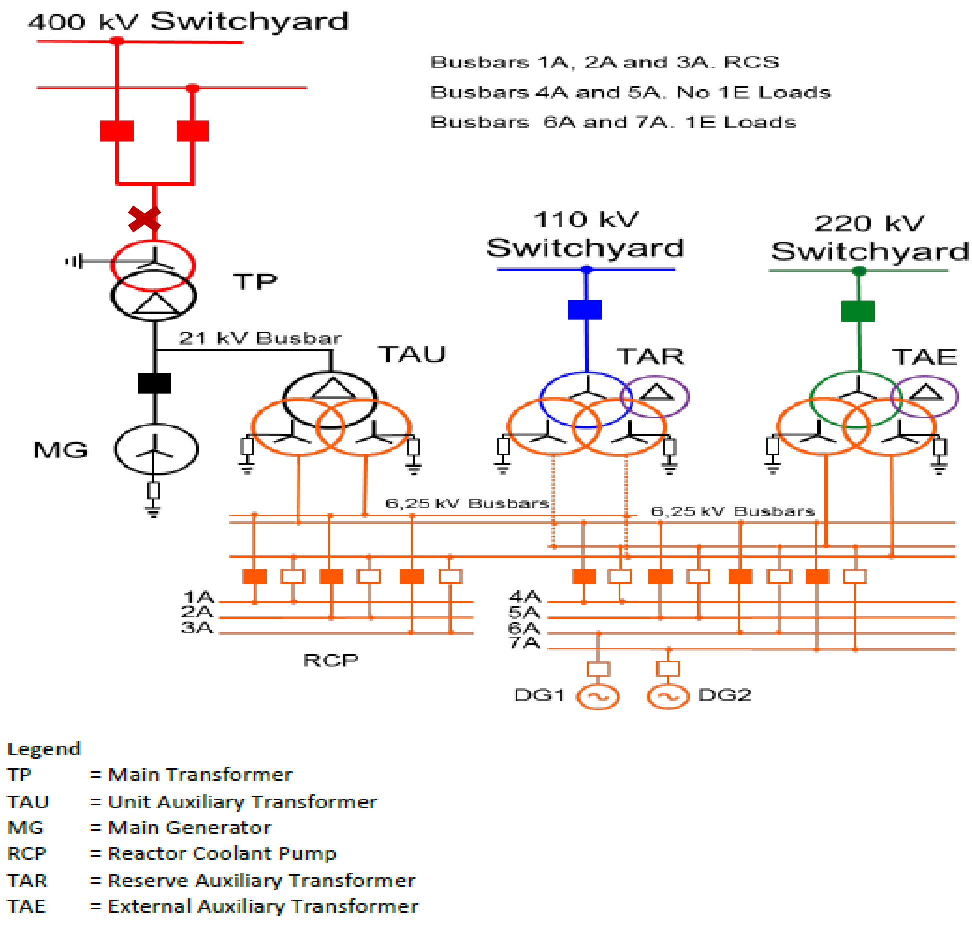


Figure A- 10 Vandellòs Unit 2 electrical diagram [33]

- ***EVENT DETAILS***

On the 9th August 2006, at the Vandellòs NPP Unit 2, an Open phase condition occurred due to a loose cable connection. The 'R' phase cable came loose on the main transformer, between the breaker and the support insulator. The protection sensed a phase mismatch between the phases of the main generator and initiated an automatic reactor scram and turbine trip [33].

Soon after the trip, an operator noticed that the main transformer is only supplied by two phases; the Open phase condition was discovered after a walk-down in the switchyard. An investigation revealed that the OPC resulted from the rotating annular contact of the insulator that burned off. **indicates that the fault occurred on the HV side of the main transformer.

A two-column rotating breaker is installed on the 400 kV switchyard side of the connection to the transformer. The HV breakers are made up of three single pole-single mechanisms. Each made up in turn by a metallic chassis. "*The support insulators, which support the main breaker current line, are attached to this chassis via the respective bearings. At the upper part of these support insulators there are fittings on which the current line is mounted. The current line is made up of the main blade and annular rotating contact.*" [33]

There was no single open phase protection installed in the NPP, hence the OPC was not detected. The lost phase 'R' voltage was regenerated by the other two phases. The loads supplied by the TAU did not get damaged during this event, as the unbalance was present for a short duration.

- ***CAUSE OF OPC***

The Open phase condition occurred due to a loose connection on the 'R' phase between the 400 kV support insulator and the HV side of the main transformer breaker. The rotating annular contact on the insulator burned off [33].

A2-4 DUNGENESS B UNIT 22, UK, 27 APR 2014

- ***STATION LAYOUT***

Unit 22 has the same station layout, see section 3.3.2 1, see Figure 3-11 and Figure A- 11.

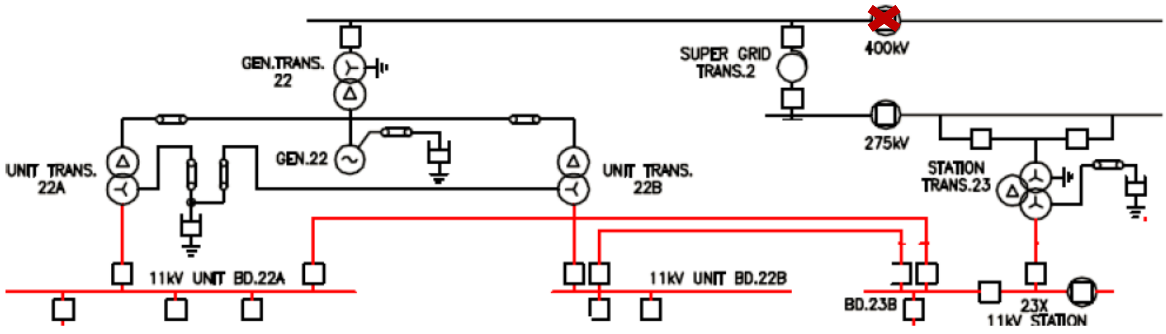


Figure A- 11 Single line diagram of Dungeness Unit 22 [33]

- ***EVENT DETAILS***

On the 27th April 2014 (7 years after the OPC on the SGT1 of Unit 22) in the 400 kV switchyard at Dungeness B Nuclear power station Unit 22, a dormant defect caused an open circuit in the 400 kV Bus coupler breaker. The defect was hidden as long as there was a parallel path available from the other Unit. When the parallel path was removed due to planned switching, a negative phase sequence alarm came up in the Dungeness B Unit 22 main control room as well as by the TX system operator [2]. The system operator followed their procedures to separate the last equipment that was switched and to assess event details. The alarm indicated that there was an OPC and the 275 kV local network was only supplied by two phases and the open phase was on the blue phase of the 400 kV Bus coupler breaker [33]. The NPS protection tripped Generator Unit 22 and automatically sent a signal to scram the Unit. It was found that the blue phase 400 kV Bus coupler breaker pole did not make "adequate contact" [15].

At the time of the trip, Unit 22 was operating at its normal power output and Unit 21 was on outage. After a few minutes the gas circulator motors called the "very low and speed pony motors-VLSPMs" and the cooling pumps of the main vessel tripped on overcurrent, along with other motors for low voltage pumps, tripped on overload thermal protection [2]. On Unit 21 the surge pumps tripped due to "extreme low levels", as well as the gas circulators 23 and 24. The forced reactor cooling on both Units were lost after Unit 22 tripped. The boiler feed was also offline for 15 minutes, but no increase in temperature was observed in Unit 21 as the decay heat was low due to the reactor being shut down for weeks before the incident occurred [33].

Other electrical equipment was also affected and tripped i.e. essential cooling water recirculation (ECWR) and automatically restarted using diesel drives and the heating and ventilation (H&V) systems.

Operators found it challenging to diagnose this incident, as there were insufficient indications in the control rooms. Approximately 10 minutes after the Unit 22 trip, they observed the varying voltages on the 11 kV station boards in the central control room. These 11 kV voltage indications were reflecting the incident on the 400 kV/275 kV switchyard and revealed to the operators that there was an "ongoing grid disturbance" [33]. The shift manager resolved that the supply from the grid was not reliable and isolated by opening the breakers to the 3.3 kV EDG boards. Operators started Unit 22 VLSPMs using the backup (BU) supplies. These tripped after closing, as the BU was still grid supplied. The cooling pumps automatically restarted and stayed in service. The

3.3 kV boards supplied by the BU diesel generators were separated from the grid supplies, which then gave a steady three phase voltage output.

A grid operator identified the OPC in the 400 kV bus coupler breaker circuit and isolated the bus coupler. The electrical system was returned to its normal configuration over a period of time.

- ***CAUSE OF OPC***

The Open phase condition occurred due to a latent defect that was present in the 400 kV bus coupler blue phase breaker. The latent defect was due to the blue phase breaker pole not making proper contact. The open circuit in the breaker was due to a “maintenance induced defect” [2].

A2-5 BALAKOVO UNITS 1 AND 3, RUSSIA, 25 FEB 1997

- ***STATION LAYOUT***

The Balakovo nuclear power plant is situated in Balakovo City, Saratov Oblast, approximately 900 km from Moscow in Russia. BNPP is owned and operated by ROSENERGOATOM, which is the Russian Atomic Energy Ministry [50]. There are 4 reactor Units, which are Water-water energetic Reactors (VVERs) each with an output of 1000 MW [51].

- ***EVENT DETAILS***

On the 25th February 1997 in the 220 kV switchyard there was a short circuit in the HV breaker phase 'A' of Unit 1 main transformer, T-1. At the same time Unit 3 was experiencing spurious trips and the bus duct electrical protection caused a LOOP and their auxiliary supply was lost at Unit 1 and Unit 3. The EDGs then automatically switched in. The OPC resulted in damage to four 6 kV motors and eleven 400 V motors [2]. Protective relays operated to clear the short circuit and Unit 1 main generator was separated from the faulty section.

The short circuit on one phase developed into a two-phase earth fault. At the same time, the 'A' phase contact closed spontaneously on the HV breaker, which resulted in an asymmetrical voltage condition which propagated to the onsite power system.

After investigation it was found that the spurious trips operated by the bus duct protection of Unit 3 was due to an undetected earth fault in the phase 'B' current transformer (CT) of Unit transformers 3T-1 and 3T-2 [2]. This undetected earth fault was not sensed by the protection, due to a design deficiency in the differential bus duct protection of Units 2, 3 and 4.

After further investigation into the breaker of Unit 1, it was found that due to an "inadequate design of the compressed air supply" [2] of the 'A' phase HV breaker, which caused insufficient compressed air and thus spuriously closing the breaker contact. The compressed air in the pneumatic system in the breaker is normally supplied by 0.4 MPa, using a U-shaped pipe. Due to the shape of the pipe, moisture gathered at the lowest part. The valve in the Unit did not remove the moisture nor did it indicate when moisture was present [2].

- ***CAUSE OF OPC***

The Open phase condition occurred in Unit 1 due to an open circuit that was present in the 220 kV HV breaker on the 'A' phase of the main transformer T-1. The open circuit was due to the "inadequate design of the compressed air supply" in the breaker that caused the breaker contact to erroneously close. The inadequate design was used in the pneumatic system which incorporated a U-shaped pipe. The shape of the compressed air pipe allowed moisture ingress and accumulation. And this in turn caused the pressure in the system to be insufficient [2].

The Open phase condition occurred in Unit 3 due to an undetected earth fault in the phase 'B' CT of Unit transformers 3T-1 and 3T-2 [2]. The CT was designed to monitor the differential protection on the Unit transformers. The CT sent a signal which caused the bus duct protection to operate erroneously. The earth fault was not detected due to a "design deficiency of differential bus duct protection" [2]. The design deficiency inhibited the detection of lost phase currents.

A2-6 KALININ UNIT 1, RUSSIA, 13 MAY 1994

- ***STATION LAYOUT***

The Kalinin power plant (KPP) is situated in Tver Oblast, Udomlya, approximately 200 km from Moscow in Russia. KPP is owned and operated by ROSENERGOATOM, which is the Russian Atomic Energy Ministry [49]. There are 4 reactor Units, which are Water-water energetic Reactors (VVERs) each with an output of 1000 MW [51].

- ***EVENT DETAILS***

Based on the IAEA report [2], on the 13th May 1994, at KPP an Open phase condition (OPC) occurred at the autotransformer (AT-1-750) of Unit 1. Reverse current sequence in the main generator was produced and activated the negative sequence current protection. The main generator and reactor tripped, and a differential protection DFZ-504 operated; this eventually led to LOOP at Kalinin Unit 1. The accumulator battery of the common DC bus lost charging power, hence the voltage dropped. Two of the inverters of the uninterruptable power supply were affected and disconnected due to low voltage, and power was lost to a number of essential loads. Parts of the main control room information board, communication system and protection panels experienced loss of supply. The OPC was caused by severe damage on a clamp at the autotransformer 750 kV phase ‘B’ which caused separation of a conductor of the 750 kV bus duct. The clamp got damaged due to a fatigue-induced fracture of the aluminium plate in the junction between the cable of the bus duct of the AT1-750 transformer and the surge arrester. An undesired operation of the differential protection DFZ-504 disconnected the off-site power to the unit standby transformer, which resulted in the loss of off-site power at Unit 1.

- ***CAUSE OF OPC***

The Open phase condition occurred due to the Autotransformer AT1-750 power cable which broke off at transformer 750 kV ‘B’ phase bushing. The cable broke due to severe damage on a clamp holding the 750 kV power cable. The severe damage was caused by a fatigue-induced fracture of the aluminium plate [2].

A3 SURVEY CONSENT FORM

Eskom

Eskom Holdings SOC Limited
Transmission Division
No 60 Voortrekker Road
BELLVILLE
7535

Date:24 May 2018

Enquiries:
Tel +27 21 915 9241

Dear Sir

Could you please be so kind and give Cindy Bass permission to conduct a survey within the Eskom organization.

The research conducted is an "Investigation of Mitigation and Detection Methods of an Open Phase Condition (OPC) in a Nuclear Power Plant based on the Operating Experience". The focus of the dissertation is to find out if the OPC can be prevented from occurring.

The target audience for this survey is 20 representatives from each of the following divisions, i.e. Transmission and Generation, specifically from nuclear generation.

The research survey will consist of a short questionnaire of approximately twenty (20) questions which will take each participant a maximum 20 minutes to complete. The survey is to assess the awareness of an Open Phase Condition.

The purpose for the research is to complete the requirements for a Master's degree in Nuclear Power at the University of Cape Town. And it is taken that the survey results may not be the view of Eskom as an organisation.

Yours faithfully

Mr Kooben Munsamy
Western Grid Manager

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Eskom Holdings SOC Ltd Reg No 2002/015527/30

A4 OPC SURVEY FORM

Dear Eskom Guardian,

I am a student of UCT, doing a Master's degree in engineering in Nuclear Power. I have the daunting task of completing a minor dissertation. The topic I have chosen to investigate is the mitigation and detection methods of an Open Phase Condition (OPC). I am working for the Transmission (TX) division, where TX substations interface with the Koeberg Nuclear power plant (KNPP). The survey aims to assess the awareness regarding the OPC, in order to improve and strengthen the relationship between TX and KNPP. OPC occurs when one or two of the electrical phases in the plant are lost.

This topic is well documented as there have been several cases that have occurred world-wide in different nuclear power plants (NPPs). However, it might not be as well known amongst people working in close relation to a Nuclear power station i.e. amongst staff of the transmission division and/or staff in the NPP. This topic is significant as an OPC has the capability of affecting important to safety equipment and has the capability to make the offsite supply inoperable.

It is kindly requested that you take 10 to 20 minutes to answer the questions below, based on your transmission and/or nuclear experience and knowledge. This survey is voluntary and anonymous and the information will be used to gauge the understanding and perception of people in the nuclear and transmission field regarding this topic. It is taken that the results of the survey may not be the view of Eskom as an organisation.

After completing the survey, please return it to the researcher personally or via email to bassca@eskom.co.za.

Thanking you in advance for your precious time and sharing your expertise in completing this valuable survey.

Warm regards,
Cindy Bass
0726539990

Questions 1-4, tick the relevant box.

A: Personal information (Information will be kept confidential)	
1. What is your gender? Male ☐ Female ☐	2. What age group are you in? <30 years ☐ 31 – 45 years ☐ >45 years ☐
3. Do you work for a Nuclear power plant or Transmission division within Eskom? Nuclear Power plant ☐ Transmission ☐	4. How many years have you worked in the nuclear or transmission field? 1-5 years ☐ 6-10 years ☐ > 10 years ☐

Questions 5-7, please answer the questions honestly, based on your knowledge and experience. Please indicate the appropriate response to the questions below.

B: OPC awareness	1 = Strongly disagree	2 = Disagree	3 = Neutral	4 = Agree	5 = Strongly agree
5. I was aware that an OPC can occur in a nuclear power plant (NPP)	☐	☐	☐	☐	☐
6. I was aware that an OPC can occur in the connecting Transmission (TX) substation	☐	☐	☐	☐	☐
7. I was aware that an OPC had occurred in Nov 2005 in the Koeberg TX GIS substation	☐	☐	☐	☐	☐

Questions 8-13, please indicate the appropriate response to the questions below and where requested, kindly provide additional information if you agree or strongly agree.

C: Design vulnerability	1 = Strongly disagree	2 = Disagree	3 = Neutral	4 = Agree	5 = Strongly agree
8. In my opinion, the Koeberg Nuclear Power plant (KNPP) is vulnerable to the OPC	☐	☐	☐	☐	☐
9. In my opinion, the concerns regarding the OPC have been adequately addressed in the KNPP	☐	☐	☐	☐	☐
10. Please provide details of how the concerns have been addressed in the KNPP:					
11. In my opinion, the Koeberg TX substation is vulnerable to the OPC	☐	☐	☐	☐	☐
12. In my opinion, the concerns regarding the OPC have been adequately addressed in the Koeberg TX substation	☐	☐	☐	☐	☐
13. Please provide details of how the concerns have been addressed in the Koeberg TX substation:					

Questions 14-20, please indicate the appropriate response to the questions below and where requested, kindly provide additional information if you agree or strongly agree.

D: International Operating experience	1 = Strongly disagree	2 = Disagree	3 = Neutral	4 = Agree	5 = Strongly agree
14. I am very knowledgeable about the effects of an OPC	☐	☐	☐	☐	☐
15. State the effects of the open phase condition:					
16. I was aware of the other OPCs that occurred elsewhere in the world	☐	☐	☐	☐	☐
17. I was aware of the international operating experience and learning's that came out of the OPC incidents	☐	☐	☐	☐	☐
18. Mention some of the operational experience that came out of the OPC incidents:					
19. I am aware of the detection and mitigation methods available currently on the market to detect the Open phase condition	☐	☐	☐	☐	☐
20. State detection and mitigation methods that you are aware of:					

A5 ADDITIONAL SURVEY RESPONSES

SECTION A: PERSONAL INFORMATION

The first four questions in section A will be graphically represented, to provide insight into the gender, age, division and years of service of the participants that responded to the survey.

- ***Q1 – What is your gender?***

Based on the participants, more than half (57 %) were male and the remaining (43 %) were females (see Figure A- 12). As per Eskom's Employment Equity goals, it has aimed to reach 50 % female employees by the year 2020 [52]. This sample is a good representation of the gender within Eskom Holdings.

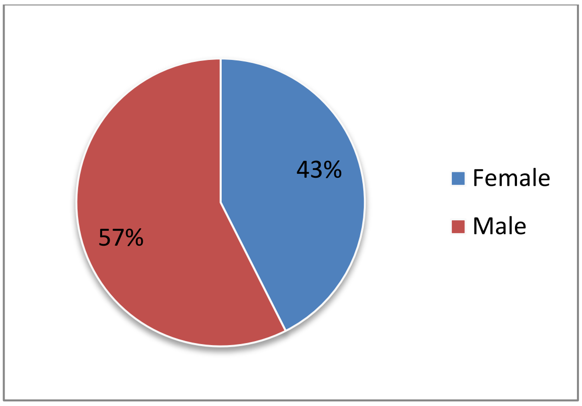

Figure A- 12 Q1 – Gender

- ***Q2 – What age group are you in?***

The participants' age group was requested, in order to assess the awareness amongst the different age groups and to see if the experience and knowledge gets passed on to the younger staff. Based on the sample of participants, 12.77 % were younger than 30 years old, 55.32 % were between the ages of 31-45 and 31.91 % were older than 45 years old (see Figure A- 13). More than 87 % of the participants were older than 31 years.

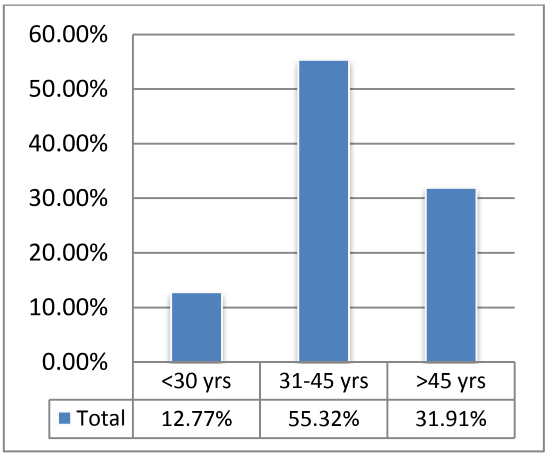

Figure A- 13 Q2 – Age groups

- ***Q3 – Do you work for the NPP (GX) or Transmission (TX)?***

KNPS is the only nuclear GX on the African continent; hence there is a unique relationship between the Western grid TX staff and KNPS. Of the participants 77 % were from TX and 23 % were from GX, see Figure A-14.

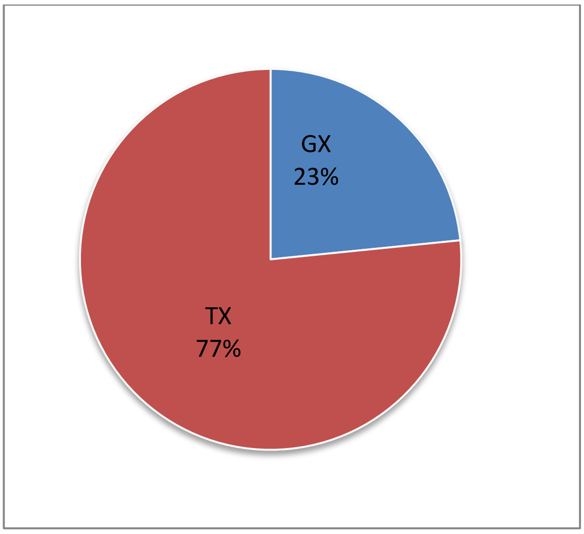

Figure A- 14 Q3 – Division

- ***Q4 – How many years of service in that division?***

The years of service in that specific division is an important parameter in this survey. The KNPS event took place in 2005, which is more than ten years ago. Hence it is expected that people with more than ten years of service (51.1 %), should be more aware of this event than those who has less than ten years of service (48.9 %) (See Figure A- 15).

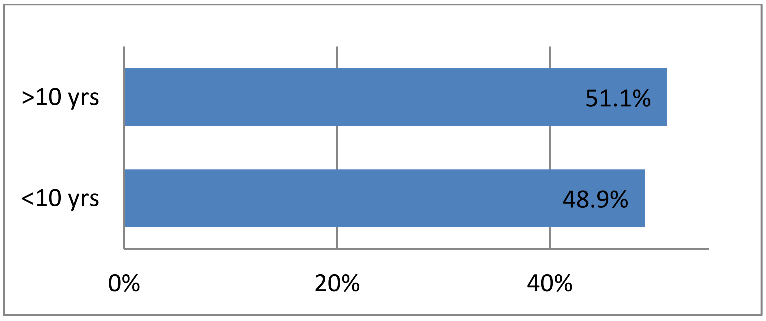

Figure A- 15 Q4 – Years of service

SECTION B: OPC AWARENESS

- ***Q5 – I was aware that an OPC can occur in a NPP***

The response to question 5 above indicates that 57.45 % of the participants were aware that an open phase event could occur in a nuclear power plant. And the remaining 42.55 % of them were not aware (see Figure A-16).

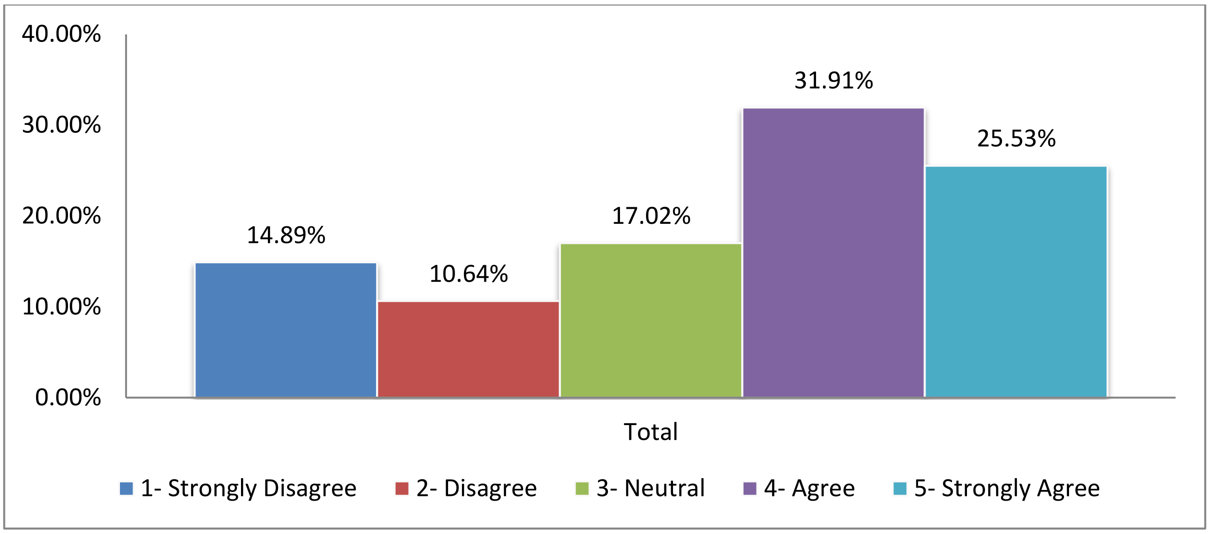

Figure A- 16 Q5 – Awareness total of OPC in NPPs

Table A-1 shows the awareness of an OPC in a NPP, which is split between generation and transmission. This analysis shows that the majority at 45.45 % of GX staff strongly agree that they are aware that on OPC can occur in a NPP and the second highest is 33.33 % of TX staff agreeing.

Table A- 1 Q5 – GX vs TX awareness of OPC in NPPs

Row Labels	1- Strongly Disagree	2- Disagree	3- Neutral	4- Agree	5- Strongly Agree	Grand Total
GX	9.09 %	9.09 %	9.09 %	27.27 %	45.45 %	100.00 %
TX	16.67 %	11.11 %	19.44 %	33.33 %	19.44 %	100.00 %
Grand Total	**14.89 %**	**10.64 %**	**17.02 %**	**31.91 %**	**25.53 %**	**100.00 %**

- ***Q6 – I was aware that an OPC can occur in the connecting transmission substation***

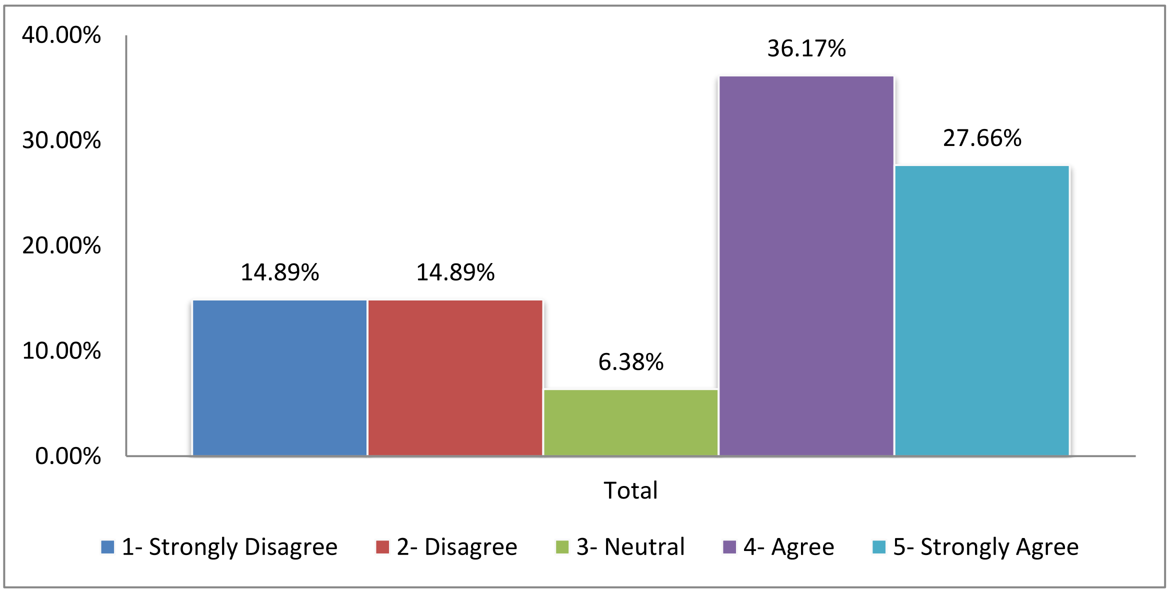

Figure A- 17 Q6 – Awareness of OPC in TX substation

SECTION C: DESIGN VULNERABILITY

- ***Q9 – In my opinion the concerns regarding OPC have been adequately addressed in KNPS***

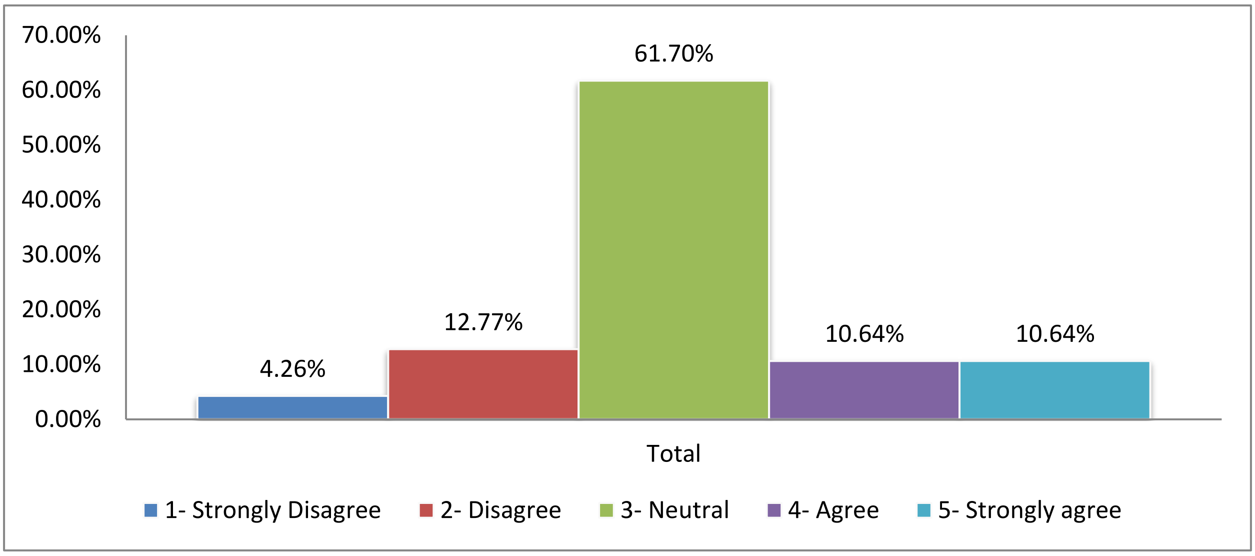

Figure A- 18 Q9 – KNPS OPC concerns were addressed

- ***Q11 – In my opinion the Koeberg TX substation is vulnerable to the OPC***

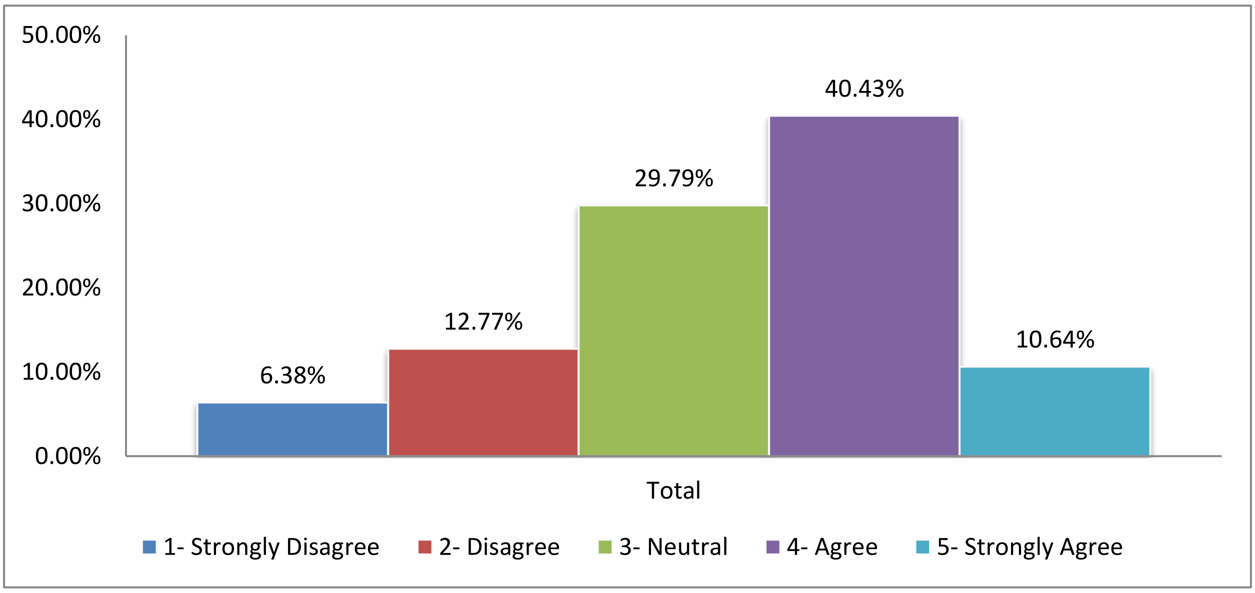

Figure A- 19 Q11 – TX substation is vulnerable to OPC

- ***Q12 – In my opinion the concerns regarding OPC have been adequately addressed in the Koeberg TX substation***

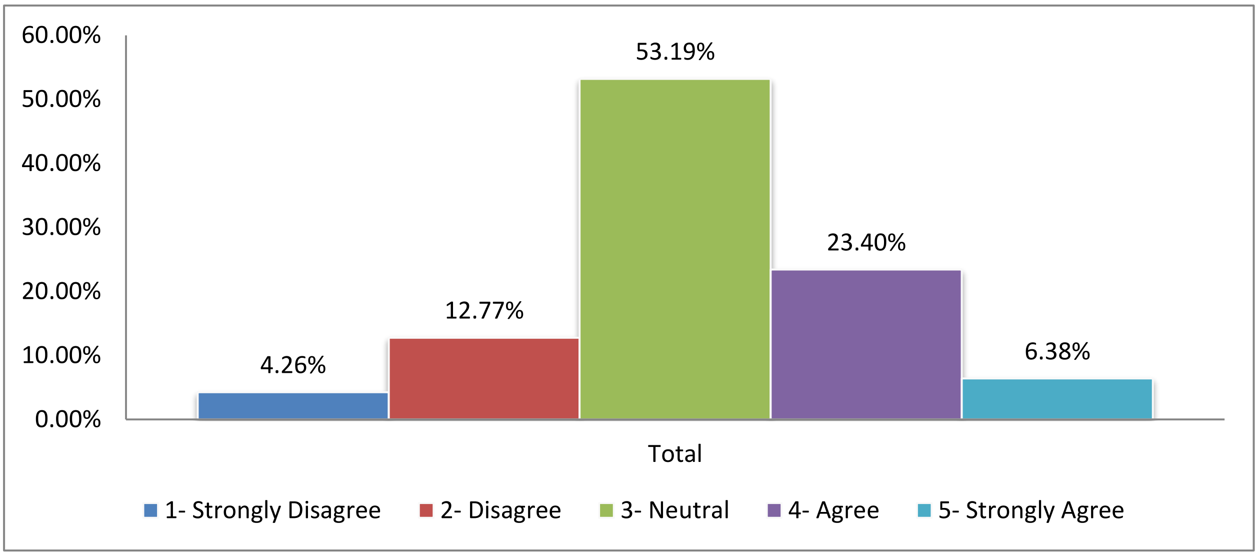

Figure A- 20 Q12 – TX substation OPC concerns were addressed

SECTION D: INTERNATIONAL OPERATING EXPERIENCE

- ***Q17 – I was aware of the international operating experience and learnings that came out of the OPC incidents***

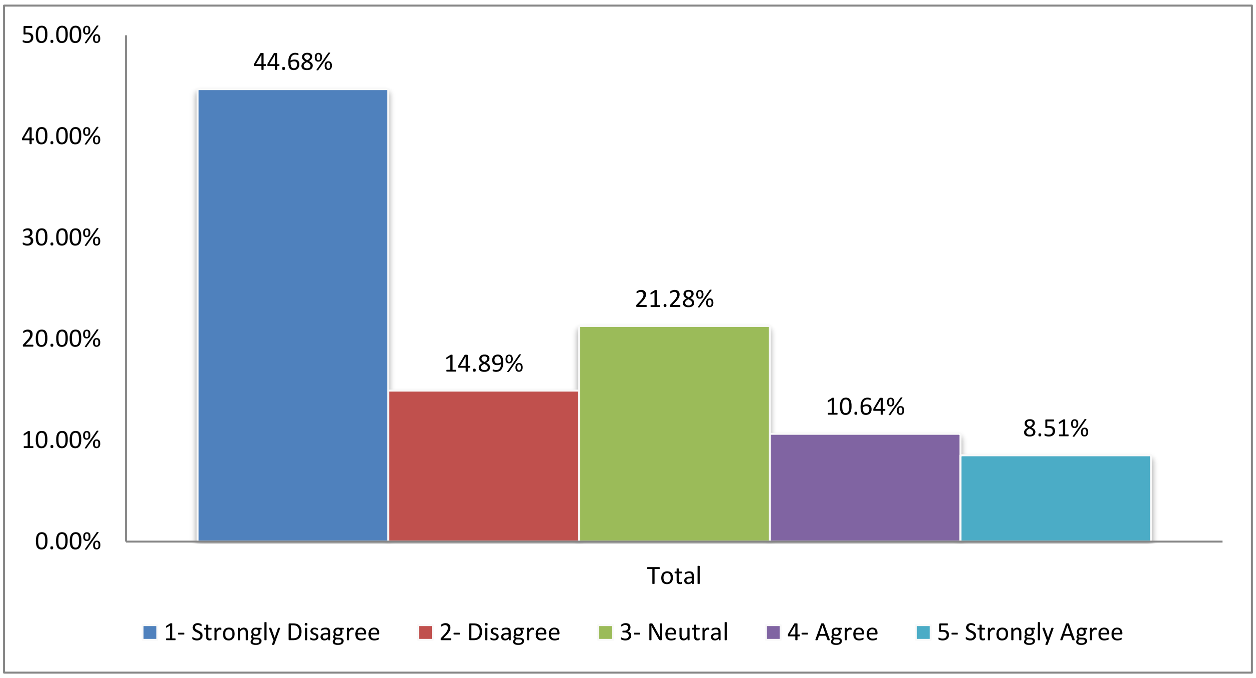

Figure A- 21 Q17 – Awareness of International OE

- ***Q19 – I was aware of the detection and mitigation methods available currently on the market to detect the OPC***

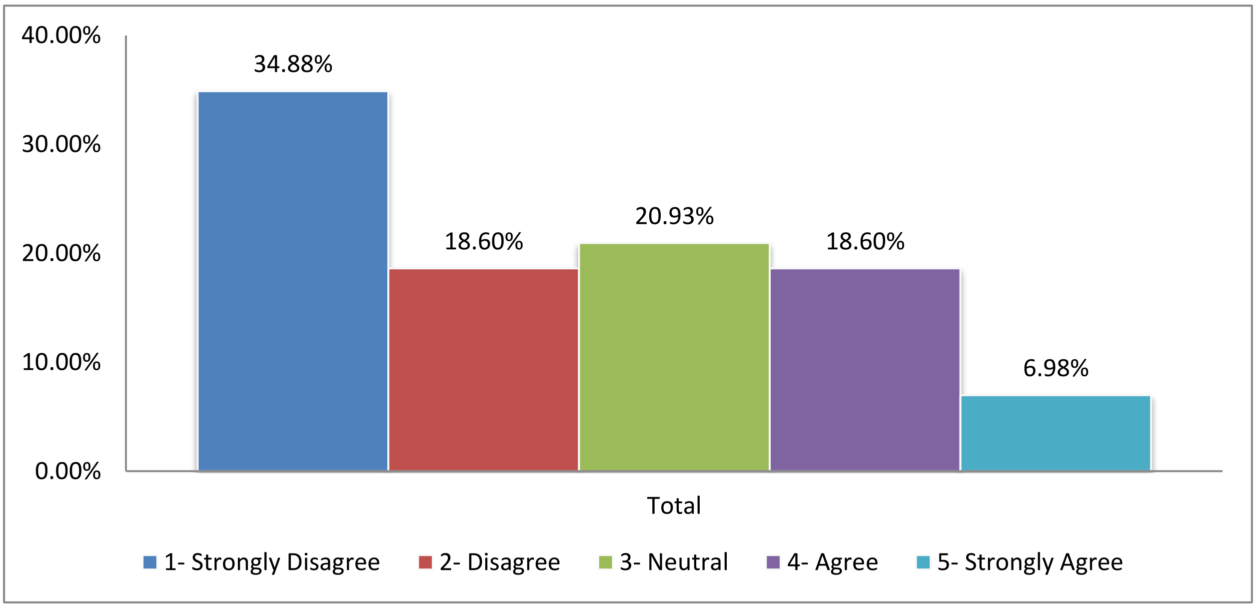

Figure A- 22 Q19 – Awareness of detection and mitigation methods